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Ubiquitous Computing at Point of Care in Hospitals: A User-Centered Approach

Thesis for the degree philosophiae doctor

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Abstract

Ubiquitous computing opens up for a wide range of ways to support human-computer interaction beyond the desktop, and promises more seamless integration between computer technology and situations of use. However, the dissemination of ubiquitous computing has been slow. Research on this type of technology has in many ways been technically motivated, rather than focusing on how it can be made practically useful. Most critical, there is little design guidance that can help technology developers apply ubiquitous computing designs and concepts to real-world use settings, and provide an understanding of how this technology presents itself to users.

This thesis addresses the applicability of ubiquitous computing in the highly dynamic work environment that hospitals form. The current work aims to inform user-centered design of ubiquitous computing solutions for hospital workers and care situations that occur at the patient's bedside.

The conducted research has resulted in five journal and conference papers (see Part II) that address various aspects relevant for the different phases (analysis, design, and evaluation) of user-centered design.

In the first paper, requirements for design methods, context models, and system properties of mobile electronic patient charts are discussed. In particular, it shows how the proceeding of events occurring in the information system and the real world relative to specific user can be used as a basis for navigation in clinical information.

The second paper investigates the affordances of paper-based medication charts out of the motivation that this can help inform design of ubiquitous computing solutions for clinical use. It shows how paper as an information medium offers affordances (and constraints) central for clinical information work, many of which are not directly transferable to digital media.

The third paper proposes a visual formalism for describing human-computer interaction in digitally augmented spaces. The paper also describes and discusses results from an expert group evaluation of the formalism.

In the fourth paper, a usability comparison of different location and token-based interaction techniques for accessing medical information at the point of care is presented. The paper identifies three user-perceived usability issues relevant for implementation of sensor-based interaction techniques in hospital settings: *required user attention*, *predictability of system behavior*, and *integration with work situation*. It also shows that the interaction techniques differ in terms of the extent to which they fulfill the above criteria, and that the usability of the various techniques is highly relative to the immediate use situation.

Lastly, in the fifth paper the usability of a location-based communication service is evaluated. The service allows hospital workers to leave short digital messages at relevant physical locations (e.g., by a patient bed), so that colleagues can access them later when entering such a location. A usability evaluation of the service indicated that participants (nurses) valued its non-interruptive means of exchanging information, and that it potentially can reduce reliance on their personal memory, when used as a personal reminder service.

Taken together the papers form a platform for future research on UbiComp technology applied in hospital work.

Contents

List of papers

MEDINFO-04
Dahl, Y., Sørby, I.D., Nytrø, Ø.: Context in Care—Requirements for Mobile Context-Aware Patient Charts. Proceedings of the 11th world congress on medical informatics (MEDINFO). IOS Press, Amsterdam (2004) 597–601

PCTH-06
Dahl, Y., Svanæs, D., Nytrø, Ø.: Designing Pervasive Computing for Hospitals: Learning from the Media Affordances of Paper-based Medication Charts. Proceedings of the 1st International Conference on Pervasive Computing technologies for Healthcare. IEEE (2006)

IASTED–HCI-07
Dahl, Y.: Toward a Visual Formalism for Modeling Location and Token-Based interaction in Context-Aware Environments. Proceedings of the Second IASTED International Conference on Human-Computer Interaction (IASTED-HCI). ACTA Press, Canada (2007) 183-192

PUC-07
Dahl, Y., Svanæs, D.: A Comparison of Location and Token-Based Interaction Techniques for Point-of-Care Access to Medical Information. Accepted for publication. Personal and Ubiquitous Computing. Springer, London (2007)

METHODS-06
Dahl, Y.: “You Have a Message Here”: Enhancing Interpersonal Communication in a Hospital Ward with Location-Based Virtual Notes. Methods of Information in Medicine. 45:6 (2006) 602-609

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) as part of fulfilling the *philosophiae doctor* (PhD) program at the Department of Computer and Information Science (IDI).

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Yngve Dahl
September 25, 2007

Part I

Context

1 Introduction

Twenty-five years ago the main focus of human-computer interaction (HCI) research was on desktop computers applied in office environments. Recent developments within mobile and wireless communication technology, however, have contributed to make computer interaction “beyond the desktop” possible, and opened up for new interactive possibilities. In many ways, the way we interact with computer technology today can be viewed as a partial fulfillment of Mark Weiser’s 1991 vision of *ubiquitous computing* (UbiComp), as described in his seminal article “The Computer for the 21st Century” [1].

Weiser envisioned that our interaction with computer technology would no longer be limited to the desktop PC and conventional input and output devices, but that we would have constant interaction with multiple interconnected computers and sensors embedded in rooms, furniture, clothes, tools, and other items that surround us. This way, persons, places, and physical objects in the world would become potential elements of computer interaction. By enabling computers embedded in the physical environments to sense and adapt to events occurring in the real world, that is, making them *context-aware*, they would effectively become seamlessly integrated with our daily activities. For interaction design, the ubiquitous computing paradigm has particularly two implications:

- The design space of interactive computer systems is expanded.
- Human-computer interaction becomes to a larger extent physical in nature.

Sixteen years after Weiser presented his vision, the interaction devices and sensor technologies for realizing it are largely available. Still, we have not achieved the seamless integration between computer technology and real-world situations, which is implicit in the ubiquitous computing paradigm. Lack of network, software, and user interface interoperability can to a certain extent explain the slow dissemination of ubiquitous computing beyond technical laboratories. However, achieving seamless human-computer interaction in and across various use situations is not only a technical problem. It also requires an understanding of how UbiComp designs are experienced by end users in situ. While conventional desktop interaction builds on the assumption that the user is sitting in front of a table with a PC and a standard set of input and output devices at his or her disposal, assumptions about the use situations, or the availability and appropriateness of interaction devices, often cannot be made for UbiComp. This again points to the need for guiding principles for accommodating the physical reality of human-computer interaction in context-aware environments.

The promise of seamless interaction with computer technology can be seen as a key motivation for research on the application of ubiquitous computing for various purposes and use settings. The current thesis addresses challenges relevant for user-centered design of ubiquitous computing in the application area of hospitals and clinical care. Extensive mobility, rapidly changing context, and the need for quick and effortless access to relevant information are some of the aspects that make clinical information work challenging for hospital personnel. The following field observation, described by Bardram and Bossen [2], illustrates some of the current difficulties that mobile hospital workers face:

…The team leader comes running around the corner. ‘‘Where is the medicine plan?’’ she exclaims. She is doing the morning round with the physician and they have come to a patient whose medicine plan is not with all the other plans which they have brought along on the trolley. She runs into the cabinet rooms where the medicine plan ought to be, then into the room for intravenous medicine and out again. It turns out that the medicine plan is with the patient's allocated nurse, who, however, has taken the medicine plan with her to another room where she was needed.

Because relevant information often is produced and made use of in situations involving mobile personnel, conventional desktop computers are inappropriate for clinical work. Likewise, providing hospital workers with mobile terminals raise new challenges due to factors like limited screen size and input capabilities, and the need to focus on the patient and the care situation.

The issues above make hospitals appealing experimental test beds for ubiquitous computing technologies and principles.

1.1 User-centered design

Given the focus on how UbiComp technology presents itself to hospital workers in typical work situations, the current research has followed what can be described as a user-centered approach. At an overall level, user-centered design consists of three phases: Analysis, design, and evaluation. A central notion in user-centered design is that the end users are to be involved throughout the design process, and thereby given the opportunity to influence how a solution takes shape [3]. For a significant part of the study this has implied evaluating UbiComp prototypes in realistic clinical scenarios with actual nurses and physicians as participants.

The aim of the conducted research is to inform user-centered design of clinical point-of-care systems[1] with context-aware capabilities.

1.2 Delimitation of scope

In order to carry out a feasible investigation of UbiComp applied in clinical care, the scope of the study has been narrowed. The extent of the current work is further specified below.

1.2.1 Clinical point-of-care situations

Work at hospital wards can be divided into various situations with distinct characteristics [4]. Some are part of scheduled routines (e.g., morning meetings, patient rounds, etc.), while others are unplanned (e.g., incidental face-to-face meetings, patient related events requiring immediate attention). Although there are many candidate hospital scenarios in which UbiComp technology may prove helpful (e.g., [5]), it has been necessary to narrow the scope of the study to concentrate on a limited set of situations that have been appropriate for practical usability testing. Accordingly, the current study has primarily focused on situations where nurses and

[1] The US National Library of Medicine MeSH defines point-of-care systems as: "*Laboratory and other services provided to patients at the bedside. These include diagnostic and laboratory testing using automated information entry*". With the introduction of mobile computers and wireless network technology in hospitals, certain services can potentially be provided by caregivers independently of their current physical location.

physicians are located at the patient bedside, i.e., *point-of-care situations*. The main reasons why point-of-care situations form suitable test candidates for UbiComp designs can be summarized:

- Point-of-care situations are fairly generic in the sense that they occur on a regular basis in hospital wards with in-patients.
- Point-of-care situations involve personnel moving between patients.
- Hospital workers often need quick and effortless access to patient related information at the point of care.
- When at the point of care, hospital workers need to have their primary attention on the patient rather than on a computer screen.
- Certain point-of-care situations can relatively easily be reconstructed in laboratories for experimental studies (Fig. 1).

Fig. 1 Usability laboratory configured to mimic a section of a hospital ward.

1.2.2 Ubiquitous computing technology

UbiComp solutions often combine interactive media (both mobile and fixed) with sensor technology. Regarding sensor technologies, the current study has mainly concentrated on technologies that fall in two broad categories based on the methods of interaction they support. The first category consists of *location-aware* sensor technologies. Location-aware sensor technologies can detect users' presence or physical position in space. This information can be used to trigger digital services or present information related to a user's current location. Examples of presence and positioning technologies that enable location-based interaction include GPS, WLAN positioning, and Bluetooth.

The second category consists of *token-based* sensor technologies. Token-based sensor technologies can be used to scan tangible objects or artifacts containing references to digital information. Examples of token-based sensor technologies include barcode readers and tags.

In terms of interaction design, location-aware and token-based sensor technologies are highly relevant because they allow for two methods of interaction that are conceptually different. In general, location-based input occurs in the *background* of a user's consciousness, and system response is typically a consequence of entering the detection area of a location sensor, rather than the result of a deliberate action taken by him or her. Token-based input on the other hand, is to a larger extent intentional. It requires the user to temporarily shift focus from his primary objective each time he or she needs to scan a token to access the associated information. Thus, token-based interactions generally correspond to *foreground* interactions. The distinction between foreground and background activities, and its relevance in interaction design is further discussed by Buxton [6].

Both location and token-based interaction techniques have been extensively used in previous ubiquitous computing research.

Concerning media, only off-the-shelf non-customized products (e.g., PDAs with WLAN and barcode readers, and touch sensitive screens) have been used as part of the experimental laboratory tests.

1.2.3 Integration with hospital information infrastructure

Ubiquitous computing in hospitals is often described as a supplement to existing clinical information systems, e.g., providing alternative means to access medical information [5], or support for interpersonal communication [7]. To achieve this beyond limited experimental trials, however, requires large-scale integration with existing hospital information infrastructure, such as electronic patient record (EPR) systems. The issue of such integration is outside the scope of this work.

1.2.4 Socio-technical design

UbiComp designs are often built to adapt to people and use situations. In practice, however, people and practices also tend to adapt to new technology [8]. Reddy et al. [9] suggest that wireless technologies can influence established clinical communication practices. Coiera [10] argues that health systems are socio-technical systems where the organizational and the technical cannot be developed separately.

The current thesis primarily concentrates on how UbiComp solutions are experienced by hospital workers at an individual level. Neither the employed approach nor the collected evidence described in the research papers allows for conclusion regarding impact on an organizational level to be drawn. The main rationale for the focus on individual user experience is that we need to understand the more simple effects of UbiComp in hospitals and at the point of care before we can understand the more complex ones.

1.2.5 Methodology

Mobile and ubiquitous computing have raised new requirements concerning methods for testing and assessment of such solutions [11-15]. Recent studies have argued for the use of alternative approaches that put focus on how off-the-desktop solutions present themselves to users in situ. Role-playing [16] and scenario-based design [17] are examples of methods that aim to help capture and understand how mobile and ubiquitous computing designs can fit ongoing use situations. While role-playing and scenario-based design have motivated much of the approach used to gather research data for the current study, this thesis does not aim to make a methodology evaluation of these techniques with regard to UbiComp designs for hospital use.

The focus concerning methodology in the thesis has been on ways of modeling the interaction between the user(s) and the system. This has been driven by a need for visual formalisms that make it possible for system developers to model the physicality of the systems. The full motivation for this part of the work can be found in IASTED–HCI-07.

1.3 Thesis structure

This thesis consists of two parts. Part I serves as an introduction to, and synthesis for the paper collection found in Part II.

Part I defines the problem area (Sect. 2), describes the research area of ubiquitous computing (Sect. 3), and presents the employed research methodology framework (Sect. 4). Next, a brief presentation of the research results described in the individual papers is given (Sect. 5). This is followed by a description of how the strategies employed to gather research data for the papers relate to the presented research methodology framework (Sect. 6). Subsequently, the contributions of the current work in terms of informing a user-centered design process for UbiComp in hospitals is specified, and the related implications are discussed (Sect. 7). Lastly, conclusions are drawn and directions for future work are suggested (Sect. 8).

The paper collection in Part II consists of five thematically linked journal and conference papers that address various aspects of UbiComp applied in clinical care. The subjects addressed in the individual research papers can be summarized:

- Requirements for design methods, context models, and system properties of mobile electronic patient charts (MEDINFO-04).
- Medication charts and media affordances (PCTH-06).
- A visual formalism for modeling location and token-based interaction in context-aware environments (IASTED–HCI-07).
- A usability comparison of location and token-based interaction techniques for access to medical information at the patient's bedside (PUC-07).
- The usability of a location-based asynchronous communication service supporting informal information exchange between hospital workers. (METHODS-06)

2 Defining the problem area

Rather than starting out with a concrete hypothesis and performing confirmatory studies, the conducted research has been exploratory in nature. This has resulted in a set of papers (see Part II) that addresses different aspects of ubiquitous computing applied in point-of-care situations. The papers are thematically related in the sense that they deal with the different phases that comprise user-centered design.

2.1 User-centered design

2.1.1 Background

User-centered design refers to a philosophy and a set of methods where knowledge about users and their involvement in the design process is central. The degree of user involvement may differ with various methods. In some cases users are consulted at specific times during the design process. Other methods imply a more continuous involvement of users, by adopting them as partners throughout the entire design process. Approaches in which users have deep impact on the design process are often referred to as participatory design [18, 19], or the Scandinavian approach [20].

User-centered design was first applied as a large-scale software design methodology to get feedback on the usability of the graphical interfaces designed for the Xerox “Star” workstation in late 1970s. Norman and Draper popularized the term through their book *User-Centered System Design: New Perspectives on Human-Computer Interaction* [21], and Norman drew further on the concept in *The Psychology of Everyday Things* (*POET*) [22].

2.1.2 Human-centered design process (ISO 13407)

The general process for user-centered design is defined in ISO 13407, *Human centered design process* [23]. As illustrated in Fig. 2, it specifies a cycle process containing four activities:

- *Specification of the context of use*—Identification of who the users are, what they will use the design for, and under what conditions.
- *Specification of user and organizational requirements*—Identification of business requirements or user goals that must be fulfilled.
- *Production of design solutions*—Design phase drawing on experience and knowledge about the users. The fidelity of prototypes typically increases with each iteration.
- *Design evaluation*—The design is evaluated against user requirements. Ideally this step involves usability testing with actual users.

Specification of use context as well as user and organizational requirements are part of the analysis phase. The remaining activities in the cycle process respectively concern design and evaluation of the product in development.

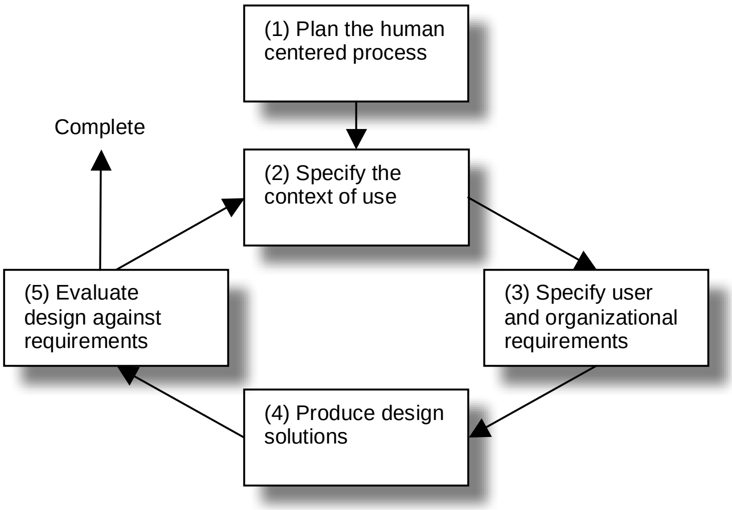

Fig. 2 ISO 13407 model overview.

Designing for practical use value is a central aim in user-centered design. This makes the concept of *usability* highly relevant. ISO 9241-11 [24] defines usability as:

The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.

To evaluate usability of a product there is, according to ISO 9241-11, a need for focusing on *who* the users of a product are, *what* they want to use it for, and *where* and in *which* context it will be used.

Together with ISO 9241-11, ISO 13407 form important usability standards. While ISO 9241-11 provides a definition of the term, ISO 13407 provides directions for how usability can be achieved. The latter standard reflects the same design principles as Nielsen's *usability engineering lifecycle* [25] (Fig. 3) in the sense that both models promote and iterative design process toward the final product, and that designers are encouraged to consider multiple design solutions (or versions) during that process.

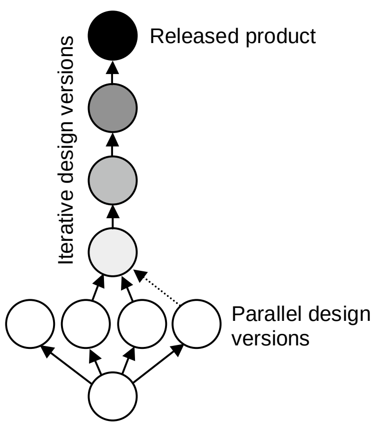

Fig. 3 Nielsen's usability engineering lifecycle [25].

2.1.3 Techniques for user-centered design

Users can be involved in design and development of a product in several ways. Abras et al. [3] describe a number of possible techniques, their rationale, and the stages in the design process for which they are ideal. The techniques include:

- Background interviews and questionnaires.
- Series of work interviews and questionnaires.
- Focus groups.
- On-site observations.
- Role-playing, walkthroughs, and simulations.
- Usability testing.
- Interviews and questionnaires on user satisfaction.

The combination of techniques employed in the gathering of research information for the individual papers in Part II is further discussed in Sect. 6.

Fig. 4 and Fig. 5 show techniques employed in the current study. In Fig. 4, a nurse interacts with a location-aware PDA as part of the experiments that were conducted to identify usability issues related to sensor-based interaction techniques (PUC-07). Fig. 5 shows an expert group evaluation that was carried out to assess the applicability of the interaction modeling formalism that was developed during the study (IASTED–HCI-07).

Fig. 4 A nurse interacting with a location-aware PDA during one of the usability tests.

Fig. 5 Collaborative modeling exercise around the visual formalism developed as part of the current study.

2.1.4 The motivation for user-centered design of UbiComp solutions

Many UbiComp designs associated with earlier studies have arguably been demonstrators of sensor technology, rather than means to explore how users experience the technology, and the extent to which context-awareness and sensor technology enriches the user experience or makes for better interactive experiences. This "technocentric" focus has been subject to criticism claiming that context-aware technology tends to be based primarily on designer-supposed usage, and on what Lueg [26] describes as developers' *approximations*, or rough estimations, of future situations of use. Lueg (op cit.) suggests that this tendency contributes to an apparent gap between *vision* and *feasibility*—that is, what *can* be built, and what is *useful* to build. Thackara [27] expresses a similar view in an article on the design challenges of pervasive computing, and argues that technological innovations often tend to be detached from the context of daily life. This detachment from users and their needs can be viewed as a reason explaining why, as pointed out by Bardram [5], ubiquitous computing often appears as "*a technology looking for a purpose*".

Employing a user-centered approach can be viewed as a means for enhancing the practical usefulness of UbiComp designs.

2.2 Guiding research issues

As previously noted, the current work addresses the applicability of ubiquitous computing in clinical point-of-care situations as perceived by end users (i.e., hospital workers), with the intention of informing user-centered design of future UbiComp solutions for this application area. The following guiding research issues aim to give a more precise idea of the contributions of the research papers and the current thesis:

RI1) *to identify requirements for digital media and navigation models supporting access to medical information at point of care.*

RI2) *to develop a practically applicable modeling technique that allows location-aware and token-based interactive systems to be described from the perspective of users in situ, with a focus on the physicality of the use situations.*

RI3) *to identify the main usability issues of interaction techniques and services associated with ubiquitous computing, in relation to clinical point-of-care situations.*

As shown in Fig. 6, the research issues above address different activities of the user-centered design cycle process. RI1 is relevant for step 2-3 (analysis phase), while RI2 and RI3 respectively concern step 4 (design phase) and step 5 (evaluation phase).

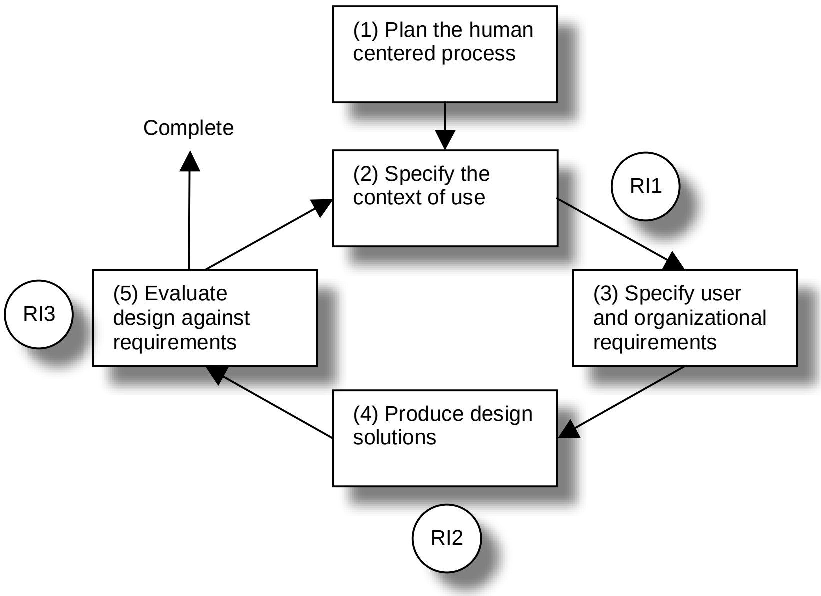

Fig. 6 The research objectives and their relation to the human-centered design process (ISO 13407).

2.3 Relevance

Over the last two decades desktop computers have become standard office equipment and contributed to increase office work efficiency. Combined with contemporary windowing systems, desktop computers have *physically* standardized information work. Information that formerly was physically distributed (e.g., paper-based information), and which required people to change physical and social contexts to retrieve and exchange, can now be accessed locally from a desktop PC.

In contrast to office work, clinical work is inherently mobile [2]. This implicitly raises the question if clinical work is suited for the physical standardization of activities that the desktop computer interaction model implies. Physicians and nurses have to move between patients who are physically distributed, be able to physically interact with the patients, and to get in touch and exchange information with fellow colleagues who are sensitive to interrupts. This can suggest the need for a paradigm shift away from the traditional way computer technology has been thought to support clinical work. The primary concern has been on how information is encoded, represented, and processed inside the computer system, largely independently of the physical and social setting in which the computer system is used. In many ways, this is comparable to how computer technology has been applied in office settings.

In an analysis of medical errors caused by Electronic Patient Record (EPR) systems, Ash et al. [28] found that a considerable number of medical errors were related to retrieving and entering correct patient information. They found this class of medical errors to be caused by (1) human–computer interfaces that are unsuited for the highly interruptive use context of hospital work, and (2) the cognitive excess caused by the number of steps that has to be taken to retrieve the correct information. The findings of Ash et al. (op. cit) implicitly raise the question of how IT solutions can support real clinical behavior—a question that is highly relevant for interaction design.

The above can in many ways be seen as an incentive to provide hospital workers with computer technology that supports mobility, and that is more adapted to an event-driven work environment. Supporting seamless integration between computer technology and situations of use is at the heart of ubiquitous computing. Ubiquitous computing provides IT systems with what can be understood as a physical user interface (this may co-exist with graphical user interfaces). Over the last quarter century, the HCI community has contributed to develop a well-established understanding of how to design user-friendly screen-based interfaces for conventional desktop computers. In comparison there is little practically applicable design knowledge on how to design physical user interfaces for ubiquitous computing.

2.3.1 The applicability of ubiquitous computing in hospitals

This section describes related aspects of medical work that can be viewed as motivational factors for applying ubiquitous computing in hospitals and at point of care. In order to give a systematic account of factors identified in relevant literature, they have been divided into four categories—*Extensive local mobility*, *interuptiveness*, *situational awareness*, and *temporality.*

The following subsections will also refer to example designs that have addressed the various issues.

Extensive local mobility

Application areas that are characterized by mobility and rapidly shifting contexts have typically appeared as strong cases for context-aware and ubiquitous computing. Context-aware and ubiquitous computing in general build on the premise of changing use situations, and mobility is often the cause of such change.

Hospital wards are characterized by extensive mobility. Bardram and Bossen [2] argue that the reason why hospital workers are constantly on the move is their need to access physically dispersed people, places, knowledge, and shared resources. This type of mobility, occurring within a limited physical area, or within a person's *action range* [29], is often referred to as *local mobility* [30, 31].

Bardram and Bossen (op. cit.) point out that the mobility of persons and artifacts in the hospital tends to have a reproductive effect in the sense that one is required to move around and actively look for the specific personnel, patients, and objects that are also moving from place to place.

Constant mobility can in many ways be considered a key incentive for providing hospital workers with point-of-care access to relevant information, by bridging the space between caregivers and relevant information with contemporary computer and network technologies. Eisenstadt et al. [32] argue that wireless communication technology is essential for timely information exchange between mobile hospital workers.

The EU-funded Ward-In-Hand project [33] was one of the early research projects to investigate the use of mobile computers and wireless access to medical information at the point of care. Examples of more recent work that has focused on the use of contextual features like hospital workers' physical position to provide point-of-care access to relevant medical information include studies around the MobileWard prototype [34] and context-aware EPR systems [5].

Interruptiveness

The hospital work environment is highly dynamic and interruptive in nature [35]. Due to sudden and often unpredicted events healthcare personnel often need to reorder their work priorities. As a consequence, their moment-by-moment activities are typically equivalent to those that have been given the highest priority.

Recent investigations suggest that hospital workers' communication behavior tend to contribute to the level of interruptions and add to inefficiency in work practice [36]. It has also been suggested that there is a relationship between the level of interruptions and medical errors [36, 37]. Communication methods that tend to increase the level of interruption are typically synchronous in nature. This applies both to face-to-face meetings and conventional telecommunication technologies, such as mobile telephony.

Alternative means of communication that take their inspiration from ubiquitous computing have been addressed in various studies. Muñoz et al. [38] suggest an approach that extends the instant messaging paradigm by letting users specify various forms of contextual information. This includes specifying the identity or the role of the recipient, the physical area in which the recipient must be to receive the message, the time period for which the message is valid, and device and artifact state for a message to be delivered.

The *AwarePhone* [7] is based on a different approach. Its aim is to reduce clinical work interruptions through context-mediated awareness about the social situation of fellow colleagues. By informing hospital workers about the *location*, *activity*, and *status* of other caregivers, the AwarePhone aims to provide individual users with a sufficient basis for selecting appropriate methods to initiate cooperation.

Situational and social awareness

As described above, issues like extensive mobility and suddenly occurring events, make conventional desktop computer interaction inappropriate for hospital workers. Another aspect that contributes to this is the inadequacy of stationary computers to allow hospital workers to keep their primary attention on the care situation and on the patients. In a recent study [39], Bardram exemplifies this by pointing out how conventional login procedures designed for conventional computer systems raise various usability issues when directly transferred to a hospital environment—the procedures do not recognize that medical work is nomadic, interrupted, and collaborative in the sense that information material often is shared.

The inadequacy of conventional desktop computer interaction in clinical work is also addressed in a study conducted by Svanæs and Alsos [40]. The study compares interaction techniques for using handheld computers with stationary displays in pre-operational briefings at the point of care.

Both studies referenced above suggest approaches that aim to let hospital workers keep their primary attention on the care situation and on the patients, rather than on the information medium. The different approaches can in many ways be considered alternative means to reduce what Bødker [41] (p. 150) describes as *focus shifts.* Focus shifts are changes in focus of attention that are more deliberate than those caused by interruptions. As pointed out earlier, Ash et al. [28] found that cognitive overload caused by the number of steps that has to be taken to enter and retrieve medical information from patient care information systems is one of the main reasons for medical errors.

Temporality

Hospital wards are highly distributed work environments, not only in the sense that caregivers often are spatially separated due to their constant mobility, but also in the sense that hospital work is distributed in time. The latter is a result of rotating shifts but also a consequence of changing work priorities causing unfinished tasks of less priority to be temporarily postponed. This means that relevant information must be passed on from one shift to subsequent shifts, and that unfinished tasks must be completed later (possibly by other caregivers).

A recent study by Reddy et al. [42] identified the need for temporal patient information among physicians and nurses working in a surgical intensive care unit. Reddy et al. use the term *temporal trajectory* to denote the structured “timeline” that activities, events, and occurrences related to a patient’s illness create. The temporal trajectory can in other words help hospital workers to put patient related information and actions into context. *LifeLines* described by Plaisant et al. [43] illustrates how the concept of time lines can be used in visual displays to enhance navigation and analysis of patient records.

Previous work on context-aware computing has identified *time* as an important piece of context information as it helps characterize the situation. Dey et al. [44] suggest that time is most relevant when used together with other types of context information as timestamp or time span.

2.3.2 Benefits of research

The factors identified above suggest that there is a potential two-way benefit between the research field of ubiquitous computing and hospital wards as application domain. On the one side, hospital workers may benefit from alternative methods of computer interaction offered by ubiquitous computing. On the other side, context-aware and ubiquitous computing build on the premise of changing use situations, making hospitals and point-of-care situations attractive for UbiComp technology.

A recent review [45] shows that relatively few research groups focus specifically on the application of ubiquitous and context-aware computing in health care. This can serve to indicate the novelty of the current work and its relevance for adoption of ubiquitous computing in professional work settings such as clinical settings.

3 Research tradition

This chapter briefly describes the background of the research field of ubiquitous computing. It will also discuss the notions of *context* and *context-aware computing*, which are strongly associated with that line of research.

There are various terms that are used to refer to the line of research that the current work follows. Frequently encountered terms include ubiquitous computing, pervasive computing, context-aware computing, and mobile computing. Lyytinen and Yoo [46] suggest that there are conceptual differences between the various programs, and that each program has different ways of organizing and managing computer services. Ubiquitous computing builds on the idea of high device mobility, and that the applications running on these devices are able to adapt to changing environments as they are carried around by users. Pervasive computing, on the contrary, is based on the idea of embedding computer technology in the physical environments in which we move, and that these embedded computers are able to detect and respond to changes in their local environments. While the idea of adaptation to changes in the environment is central in both ubiquitous and pervasive computing, Lyytinen and Yoo (op. cit.) point out that this is not a concern in conventional mobile computing.

At an overall level the lines of research described above still share the basic idea of supporting human computer interaction in various activities and various physical environments. Dourish [47] argues that it is the concept of *embodiment*, i.e., real-time, and real-space presence and participation in the world, that ties the various research lines described above together. As such, the concept of embodiment draws attention to both the physical and the social aspects of use situations.

3.1 Ubiquitous computing

More than fifteen years have passed since Mark Weiser introduced his vision of *ubiquitous computing*, predicting how our interaction with computer technology would change in years to come. Weiser saw it as a fundamental use criterion that technology allows itself to fade into the background of the users' attention. A central notion in the ubiquitous computing paradigm was to integrate computers seamlessly into our everyday physical environment. Thus, Weiser envisioned a new interaction paradigm where the world itself would become an interface mediating between users and computer technology. By enabling these embedded computers to automatically sense and adapt to their use context, they would effectively become "invisible" in use. Accordingly, the background of ubiquitous computing has both a technical and a social aspect.

The ubiquitous computing paradigm, or *third paradigm* computing as referred to by Allan Kay [48], separates itself from previous interaction paradigms both in terms of the underlying interaction model, points of interaction, the number of computers we use, and types and appearances of computer devices we interact with. Table 1 shows the conceptual differences between the various interaction paradigms.

Interaction paradigm	Era	Computer devices	Cardinality	Model	Point of interaction
Mainframe computing	mid 1960s – ca. 1980	Mainframes	N users – 1 computer	Centralized	Corporations and larger organizations (universities, hospitals, etc.)
Personal computing	ca. 1980 – mid 1990s	PCs	1 user – 1 computer	Distributed	The desktop in the home or in the office.
Ubiquitous computing (“third wave”)	mid 1990s –	Interconnected laptops, tablet PCs, PDAs, mobile phones and “gadgets”.	N users – N computers	Distributed and interconnected	“Anywhere, Anytime”

Table 1 Conceptual view of the three paradigms that have shaped human-computer interaction.

3.2 Context-aware computing and the notion of context

3.2.1 Context-aware computing

The concept of *context-aware computing* or *context-awareness* plays a central role in the ubiquitous computing program. Schilit and Theimer [49] used the term *context-aware computing* to refer to software that were able to adapt to its location of use, physically proximate people and objects, in addition to changes to those objects occurring over time. Imbuing computer systems and applications with context-aware or sensor-based behavior have become a frequently used approach to allow computer technology to fade into the background of the users’ attention. Often, this implies computer services that can take automatic actions on behalf of the user, such as presenting information relevant to the user’s physical location (e.g., *GUIDE* [50]).

The concept of tangible user interfaces (TUIs), as described by Ishii and Ulmer [51], can be considered an alternative approach that attempts to achieve seamless human-computer interaction through augmented physical objects that act as controls for digital media.

3.2.2 The notion of *context*

Since the introduction of the term *context-aware computing* during the early 1990s, the notion of *context* and what it entails have been intensely debated within the relevant lines of research. Numerous definitions of *context* have been suggested (e.g., [44, 49, 52-54]). Typically, these definitions specify various types of situational information (e.g., location, identity, time, activity [44]) that characterize a specific use situation.

Dourish [55] argues that the conceptualization of *context* that is reflected in these definitions, and in much of ubiquitous computing research, correspond to a positivist account of the notion. Implicit in this perspective is what Dourish describes as a consideration of context as a representational problem – the idea that context is a set of objective features or parameters that characterize a real-world activity, and that these features and activities can be digitally captured and represented in software systems.

The conceptualization of context described above is contrasted by an alternative view based on phenomenological arguments. Dourish [47, 55] and Svanæs [56] point out that this view regards context as an interaction problem as rather than one of representation. It rejects the idea that context is a stable and objective characteristic of the world or setting in which an activity takes place. Instead context is regarded an outcome or a product of an ongoing activity, and is subject to continuous individual perception and interpretation. Hence, context is considered to be inseparable from the (inter)activity in which it occurs.

The two contradicting views on context outlined above build on different ideas of what context is. Drawing on the work of Dourish [47, 55], Greenberg [57], and Svanæs [56] a comparison of the opposing perspective can be found in Table 2.

Aspects of context	**Positivist reasoning** (Context as a representational problem)	**Phenomenological reasoning** (Context as an interactional problem)
What is context?	Context is equal to information.	Context is a relational property. It refers to the relevance between an object and an activity.
How can relevant contextual features be identified?	Activities can be identified through a set of contextual features. The set of appropriate features for an activity can be defined a priori.	The set of contextual features that are relevant for a given activity is defined dynamically (i.e., throughout the activity).
What defines the degree of relevance of contextual features?	Context is stable. The relevance of any contextual element does not change.	The relevance of contextual features is relative to each instance of an activity.
What is the relationship between context and an activity?	Context and activity are separable. An activity can be identified through objective contextual features.	Context emerges from an activity and is subject to individual interpretation. Context and activity are therefore inseparable.

Table 2 Comparison of positivist and phenomenological reasoning on the notion of context.

3.3 Toward a technological realization of ubiquitous computing

In contrast to what the situation was when Mark Weiser expressed his vision more than fifteen years ago, many of the technical hardware components required to realize the ubiquitous computing paradigm are now commercially available. While early research projects such as the ParcTab project [58] required custom-made handheld computers and sensors, equivalent hardware now exists as off-the-shelf products.

Despite the recent technological development, large-scaled ubiquitous computing as envisioned in Ref. [1], is still far from being realized. We still lack the interoperability between computer devices, user interfaces, and network services, implicit in Weiser’s vision. To create realistic test scenarios it has been considered important to achieve a degree of interoperability that allows for evaluation of a UbiComp system as a whole, and not only the individual interaction elements that can be part of such a system. For the investigations that have involved practical usability testing (see PUC-07 and METHODS-06), only hardware that exists as commercial products has been employed.

4 Research methodology framework

Different approaches have been used to investigate the research questions addressed in the individual papers contained in Part II. To help illustrate the totality of the employed strategies, the framework and taxonomy developed by McGrath [59] is used.

4.1 The "strategy circumplex"

McGrath [59] structures strategies for gathering of research information into eight major strategies or settings, grouped into four quadrants. Together these strategies form a *strategy circumplex* (Fig. 7).

Of three desirable but contradicting criteria, each strategy prioritizes differently. The three criteria are *generalizability* of research evidence, *precision* of measurements, and *realism* of the situation or context being studied.

As shown in Fig. 7, each strategy is relative to two underlying dimensions – the extent to which the setting is abstract or concrete, and the degree to which a strategy is obtrusive or non-obtrusive with regard to the ongoing systems that are studied[2].

The eight different strategies or settings that form the circumplex are *laboratory experiment*, *experimental simulation*, *field experiment*, *field study*, *computer simulation*, *formal theory*, *sample survey*, and *judgement study*. For completeness a short summary of each research strategy follows.

A *field study* involves direct observations of "natural" systems, with minimal intrusion or disturbance of the system. Examples of this strategy include cultural anthropology and case studies of organizations.

A *field experiment* also involves on-site observation of a real-world system, but in contrast to field studies an important feature of the system is manipulated to assess the effects. A study of how new communication technology affects communication patterns in an organization is an example of how this research strategy can be used.

In a *laboratory experiment* the situation or setting is constructed, and rules for its operations are defined. Participants are then introduced to the constructed situation or setting. A conventional usability test, in which a specific set of users is given particular tasks to complete in a controlled environment, exemplifies this strategy.

In an *experimental simulation* one attempts to combine the precision and control associated with laboratory experiments, with the realism of field studies. This is typically achieved by constructing a situation or context (as in laboratory experiments), but at the same time attempting to let the simulated situation reflect much of its real-world counterpart. Ground-based flight simulators and combats or contests that are simulated in natural-like environments for purposes of research are examples of experimental simulations.

A *sample survey* concentrates on gathering data that allows the researcher to estimate how specific variables (and possibly their relationship) are distributed within a given population. Typically, this strategy involves careful selection of respondents, and systematic collection of responses. Public polls are examples of sample surveys.

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[2] In the original article [59], there is an apparent mismatch between the textual description and the illustration of the strategy circumplex with regard to its underlying dimensions (abstract-concrete and obtrusive-unobtrusive). The diagram shown in Fig. 7 is according to the correct textual description.

In a *judgment study*, the focus is on collecting information about a topic, or properties of stimulus. Judgment studies are more qualitative in nature than sample surveys, and the stimulus is typically carefully arranged. Focus group and expert group evaluations fall into this category.

Formal theory is a purely theoretical approach, and does not involve collecting any empirical data, or operation of a concrete system. Rather, the researcher uses existing theories and focuses on formulating general relations among variables of interest. General theories of behavioral and social sciences are examples of formal theory.

A *Computer simulation* is a non-empirical approach, where a real-world system and system participants are represented in a computer model. The model can simulate how changing parameters affect the real-world system. The researcher specifies the system components that are relevant, and how they interrelate.

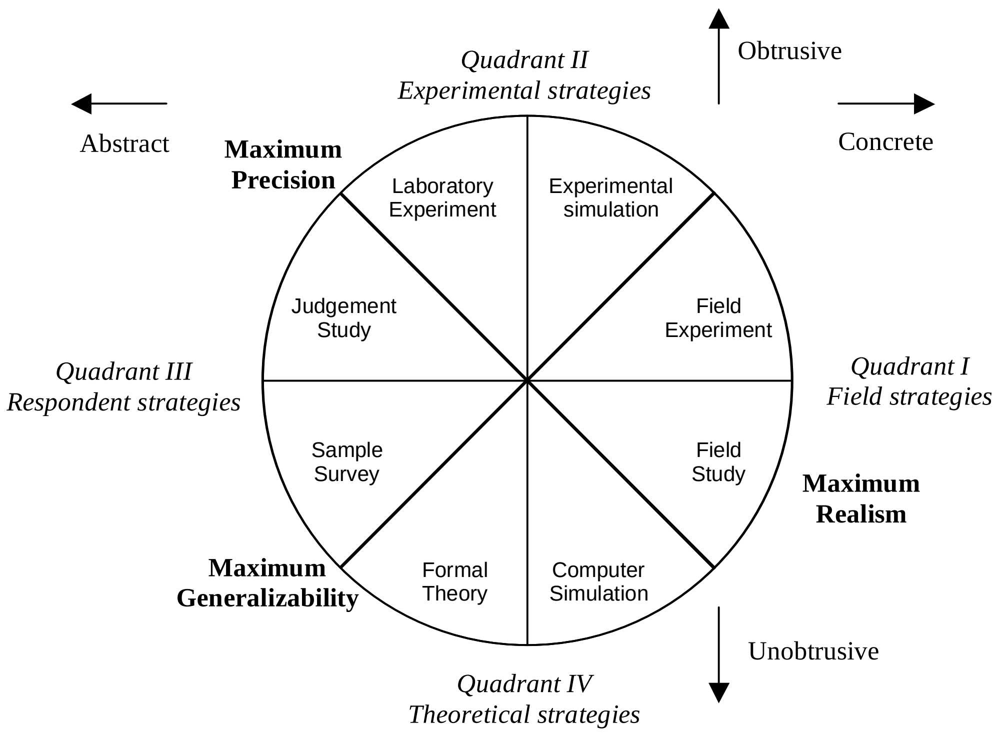

Fig. 7 The strategy circumplex developed by McGrath [59]

5 Results

This section sums up the research results of the papers contained in Part II.

5.1 Requirements for mobile context-aware patient charts (MEDINFO-04)

MEDINFO-04 is a position paper that discusses requirements for context models, design methods, and system properties of mobile electronic patient charts. In particular, it addresses how the concept of context-awareness can make relevant information more easily available on mobile electronic patient charts, and how hospital workers' changing contexts can be used as basis for navigation in clinical information.

The paper proposes a context model where the proceeding of events occurring in the information system and the real world relative to specific user, form a structured timeline of events, i.e., a *context pathway* (Fig. 9). Examples of events that may initiate a change in a context-pathway include:

- Changes in background patient information (e.g., lab test results, progression of treatment).
- Actions taken by the user (e.g., clicking a GUI button).
- Events in the physical environment (e.g., user location, proximity, patient sensor data).

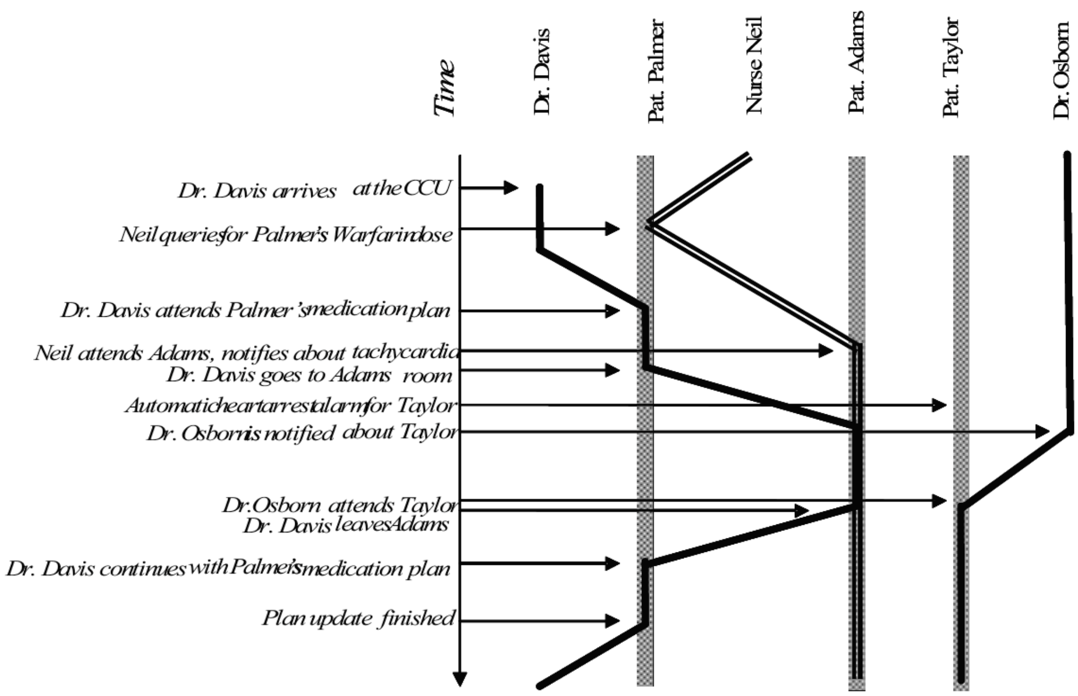

Fig. 9 Context model. Events occurring at a ward appear on the left side of the vertical timeline, while the corresponding context pathways of the different characters in the scenario are drawn on the right side.

Overlapping context pathways represent hospital-workers and patients that "share context" for a given amount of time, either physically in the real world (e.g., being colocated in a patient room) or conceptually through e.g., patient-specific activities performed on the clinical information system.

A context-pathway can be explicitly represented, and be used as a metaphor for context-based information navigation:

- A user (i.e., hospital worker) can change to a partly specified context that has occurred.
- Spool backwards through a pathway of contexts.
- A user can send a reminder to someone with an attached context.
- A user can choose to block certain (e.g., disturbing, irrelevant) context elements.
- A user can search for, and switch contexts.

5.2 Media-affordances of paper-based patient charts (PCTH-06)

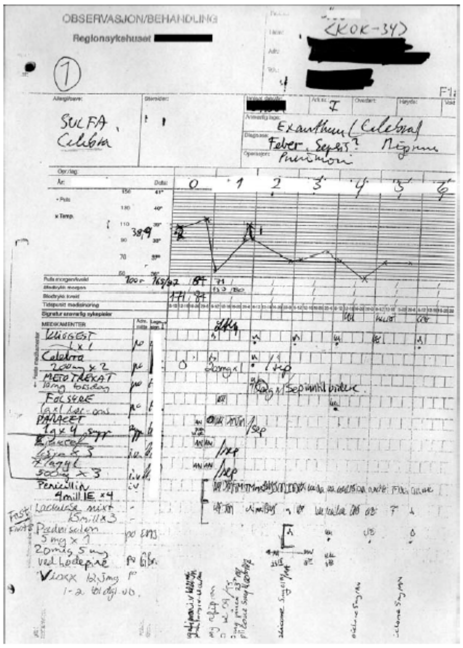

Fig. 8 Paper-based medication chart (patient-sensitive information has been edited out).

PCTH-06 identifies media-affordances offered by paper-based patient charts (Fig. 8), and compares these with affordances offered by selected digital and context-aware media alternatives.
The comparison shows that the paper chart as a medium has some unique functionalities making it highly adapted for clinical work. Drawing on a previous field observation of the role paper-based medication charts play during prescription and administration of medication, the most important affordances (and constraints) can be summarized:

- *Handability*, *portability*, and *immediacy* are essential qualities of the paper during administration. This activity is mobile in nature, takes place in locations where information work is secondary to a main activity of patient treatment or manual work involving drugs and other remedies.

- *Visible history of changes* and *uniqueness* are important in combination because it gives clues to the prescribing physician and administrating nurses, the necessary context for understanding and validating the current prescription. Aspects like authorship, responsibility, history of change, and context of decision become immediately understandable (albeit in a compact and cryptic fashion) with a paper chart.
- The chart is a *visible* and *physical token of responsibility* during the entire administration process, and gives *exclusive access* to the information, preventing changes during administration and possible risks associated with multiple administrations of the same dose.
- In the morning meeting, the medication chart acts as a vehicle for *social interaction* as it is passed around the table, and is a physical focus of common attention, i.e., a *shared display*.
- During the drug administration, *non-disruptiveness* allows focus on the critical interaction with the patient.

The paper shows that many of the functionalities above are not directly transferable to computerized versions of the patient chart. This especially applies to affordances that are related to the physical properties of paper-media. This is viewed as an incentive for investigating and providing examples of how techniques and principles associated with ubiquitous computing can restore some of the affordances and constraints associated with paper-based charts.

The paper concludes that paper-media qualities must be understood and restored in digital media in order to successfully fulfill the role paper-media still play in many hospitals today.

5.3 A visual formalism for modeling location and token-based interaction (IASTED–HCI-07)

IASTED–HCI-07 introduces a visual formalism for modeling location and token-based user interaction in digitally augmented spaces. The work described in this paper is an extension, refinement, and evaluation of the customized formalism used to identify suitable interaction techniques for the medication scenario analyzed in PUC-07. The formalism employs a similar perspective to that of storyboards in the sense that it allows for sequential visualization of interaction (Fig. 10).

The various ways the formalism helps guide thinking about accommodating physical and situational aspects of interaction, as identified through a focus group evaluation with usability experts, can be summarized:

- The formalism's notational building blocks allow designers to represent and visually compare alternative interaction design solutions for location-aware and token-based systems. Feedback from the participants indicated that it is well suited for describing combinations of interaction techniques.
- The formalism's implicit user perspective can promote reflection and discussion on design solutions.
- The expert group evaluation of the formalism indicated that the formalism was intuitive to use. The participants quickly managed to construct meaningful interaction models using the formalism as part of a collaborative exercise.

Fig. 10 Resulting model from a collaborative exercise around the developed visual formalism.

5.4 Interaction techniques for point-of-care access to medical information (PUC-07)

PUC-07 identifies four location and token-based interaction techniques that match a hospital case scenario around administration of medicine to patients. The interaction techniques combine location or token-based input with mobile or fixed output media (i.e., PDAs or bedside terminals).

Motivated by the lack of consensus concerning evaluation criteria for UbiComp systems, the different methods of interaction were evaluated with hospital workers using functional prototypes. The evaluation identifies three issues or areas of concern relevant for the user-perceived usability of location and token-based interaction techniques for point-of-care access to medical information. These issues are: *Required user attention, predictability of system behavior,* and *integration with the work situation*.

Required user attention for retrieving relevant clinical information affects usability because hospital workers need to keep their primary attention on patients and on the care situation.

Predictability of system behavior relates to the user's feeling of control over the application. Both the underlying interface models (how perceivable the elements of the physical user interface are), as well as the precision of the applied sensor technology affect this.

Integration with ongoing clinical work situations depends both on physical and social conditions of the immediate work situation. For example, test participants expressed that they often need to physically interact with patients at the point of care.

The possibility of sharing screen information with colocated patients (or hiding it from unauthorized persons) is another example of how the usability of UbiComp designs is affected by their ability to integrate with the work situation at a physical level.

Many test participants expressed that location-based techniques require less user attention (information retrieval occurs background), but often at the cost of the predictability of system behavior.

The interaction technique with the highest user preference rating was the one combining location-based input and fixed bedside terminals (Fig 12). The participants' arguments for giving this alternative a high rating were related to the ability to have both hands free, to have little focus away from the patient, and the perceived positive effect of sharing the screen with the patient.

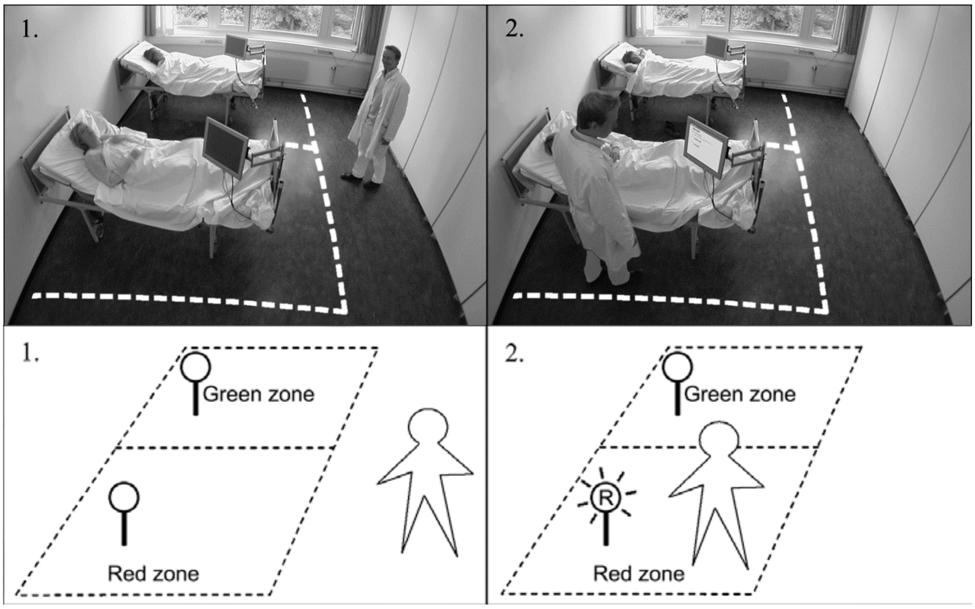

Fig. 11 Implementation of location-based interaction technique (above) and corresponding model (below).

The evaluation showed a strong variation in the test participants' preferences concerning interaction techniques. Their arguments for making their preferences were largely related to the specific physical and social conditions of the use situation. This emphasizes that the usability of a given interaction technique, providing access to medical information at point of care, is highly relative to the context of use.

This result is viewed as an incentive to consider a broad set of sensor-based interaction techniques and devices for such systems, and to select the best ones of these for implementation.

5.5 Location-based virtual notes (METHODS-06)

METHODS-06 describes a usability evaluation of an experimental communication service (*location-based virtual notes*) that allows hospital workers to leave short digital messages at relevant physical locations (e.g., by a patient bed), so that intended colleagues can pick them up later when entering such a location (Fig. 12).

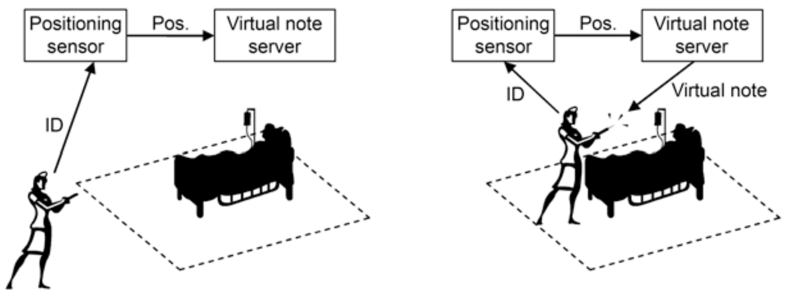

Fig. 12 Conceptual model of location-based virtual notes service.

The underlying motivation for the current service is that asynchronous interpersonal communication mediated by the physical environment, can potentially improve timeliness of information and reduce the number of work interruptions caused by synchronous communication methods. A formative usability evaluation of the service identified a number of usability issues including *the applied design metaphor*, *posting of virtual notes*, the possibility of *role-based contact*, and *user control*. Below, the most important lessons learned about each of these issues are summarized.

Metaphor: A key usability requirement concerning location-based information exchange is that users must be able to know something about how the service works. The service must be able to convey to users how it differs from other means of communication, such as instant messaging and regular e-mail. We found that the sticky note metaphor was both a familiar and a suitable allegory for informing users about the intended usage.

Posting of virtual notes: Physical objects that location-based virtual notes can be posted on should be limited to include only those that the recipients are most likely to actually interact with, i.e., elements which are more directly involved in a hospital worker's activity (e.g., patients or patient beds). This way, the location-based virtual notes will be more integrated with the overall work situation, and more likely to be attended to in due time.

Users must be informed about which physical objects a location-based virtual note is posted on in an intelligible way. Paper-based sticky notes have colors and possibly shapes that make them highly visible in the physical environment. Location-based virtual notes do not have these kinds of real affordances, and alternative means for notifying users are required. We found that short sound notifications represent one possible alternative for informing users about proximate electronic stickers. Another option could be to make the computer device the hospital worker is carrying vibrate for a short period of time.

Role-based contact: Means of role-based contact are important in order to achieve efficient clinical communication. Role-based information retrieval can therefore be seen as a highly useful feature related to the location-based virtual notes. Candidate role categories range from groups of caregivers having similar responsibilities (e.g., a nursing team), to functionalities held by one individual on a given shift (e.g., the physician on call), to roles inhabited by the current user. The last category opens up for the possibility of distributing virtual notes intended for personal use.

User control: Test participants expressed that retrieving messages from colleagues based on location or proximity should not be the only way of getting access to that information. Users should be able to create and access virtual notes anywhere and anytime at their own initiative. Following the principle of user control, a hospital worker should also have the option of requesting to be electronically notified when colleagues attend one of his distributed virtual notes.

The evaluation showed that the concept of location-based virtual notes was promising in terms of improving timeliness of informal information exchange between hospital workers. All participants expressed a perceived usefulness of the service. In particular, its non-interruptive means of exchanging information, and its potential as a personal reminder service reducing reliance on personal memory was valued.

6 Employed research strategies

This section provides an overview of the research strategies (cf. McGrath's [59] taxonomy) employed to gather research data for the different papers. It also presents some reflections concering the empoyed strategies.

6.1 A categorization of the research papers

As illustrated in Fig. 13, the research that has lead to the papers contained in Part II can be categorized according to McGrath's strategy circumplex. The only exception is MEDINFO-04, which is a position paper (presenting an arguable perspective), and does not build on direct empirical research evidence. PUC-07, METHODS-06, and PCTH-06 are based on data that has been gathered using complementary strategies.

In Fig. 13, bold types indicate the dominant research strategy. For example, when gathering research data for PUC-07, *experimental simulations* formed the primary strategy, while a card ranking (*judgment study*) was employed as a complementary strategy. It should be noted that in PUC-07 and METHODS-06, laboratory experiments and simulated scenarios are described as the dominant approaches. The papers, however, are written independently of McGrath's taxonomy. Using the categorization scheme of the strategy circumplex, the main strategy for evidence gathering for both papers corresponds to *experimental simulations.*

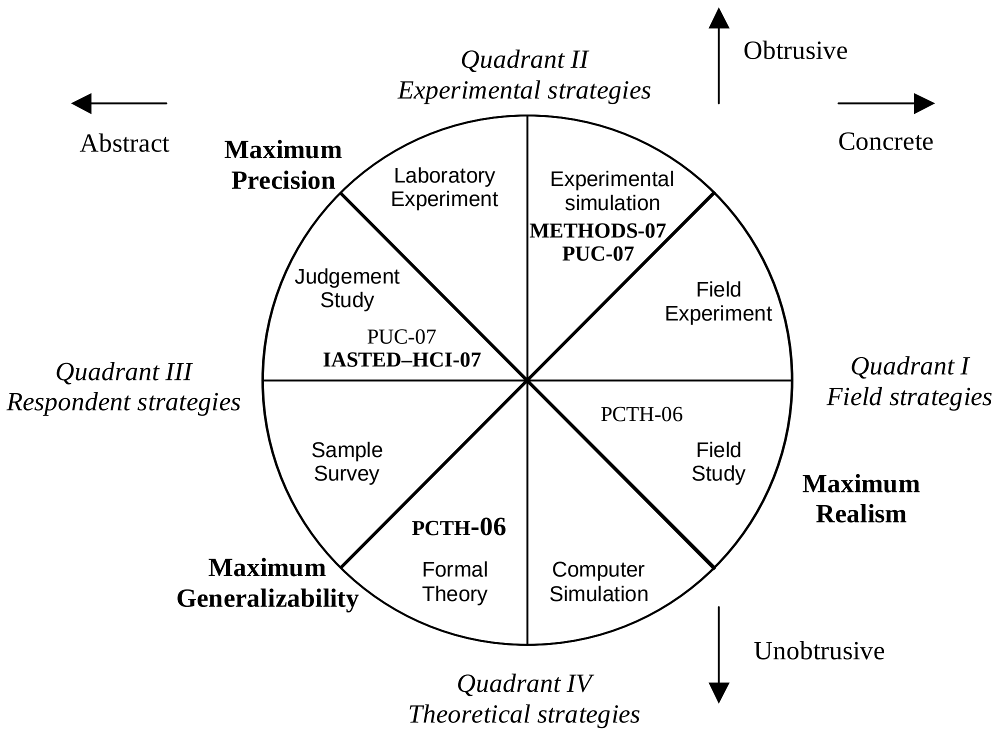

Fig. 13 The research strategies applied to gather data for the individual papers shown in relation to the strategy circumplex.

6.2 Research strategy considerations

The main argument for employing an empirical simulation strategy is, as previously noted, that one partly achieves the realism of field studies, combined with the control of conventional laboratory experiments. There are also practical issues that have lead to this approach. Instrumenting hospital wards with the necessary technical components (e.g., sensors, wireless networks, and terminals) for conducting usability testing of UbiComp systems is difficult, and is likely to interfere with ongoing work. A study by Kjeldskov et al. [60] also revealed that conducting usability evaluations in the field contra doing them in a laboratory setting provide little new insight. Moreover, the same study indicate that key aspects of the use context can be recreated in a laboratory, and help detect the same usability problems as a field evaluation would reveal.

Every usability evaluation is faced with the methodological challenge of finding the necessary level of realism concerning the use environment, the prototypes being tested, and the tasks to be performed. In order to conduct feasible usability experiments (PUC-07 and METHODS-06), the simulated work situations and the content of prototypes were simplified.

Concerning the evaluated prototypes, the overall goal was to get feedback on the various means of context-aware interaction and the physical interface of the prototypes, rather than on the graphical user interface. Such an approach is in many ways a compromise between concreteness and flexibility. It puts focus on a set of concrete solutions, but it is at the same time flexible with regard to level of detail. For example, we employed functional prototypes to exemplify context-aware interaction, but only simplified graphical representations of medical information were used.

Concerning the tasks, the focus has been on scenarios from the everyday work practice of health workers that allows us to evaluate the usability of the chosen interaction techniques and services.

Although the simplifications described above can potentially affect the applicability of the investigation and mask challenges that users meet in the real world, I consider the current approach sufficient for developing a basic understanding of user-perceived factors that affect the usability of UbiComp solutions applied in point-of-care situations. As stated earlier, the main rationale for the current approach is that we need to understand the more simple effects of UbiComp in hospitals before we can understand the more complex consequences.

7 Contributions and implications

This section discusses the contributions and implications of the conducted research with regard to user-centered design of ubiquitous computing at point of care. Fig. 14 gives an overview of which of the different activities of the user-centered design the different research papers primarily contribute to inform.

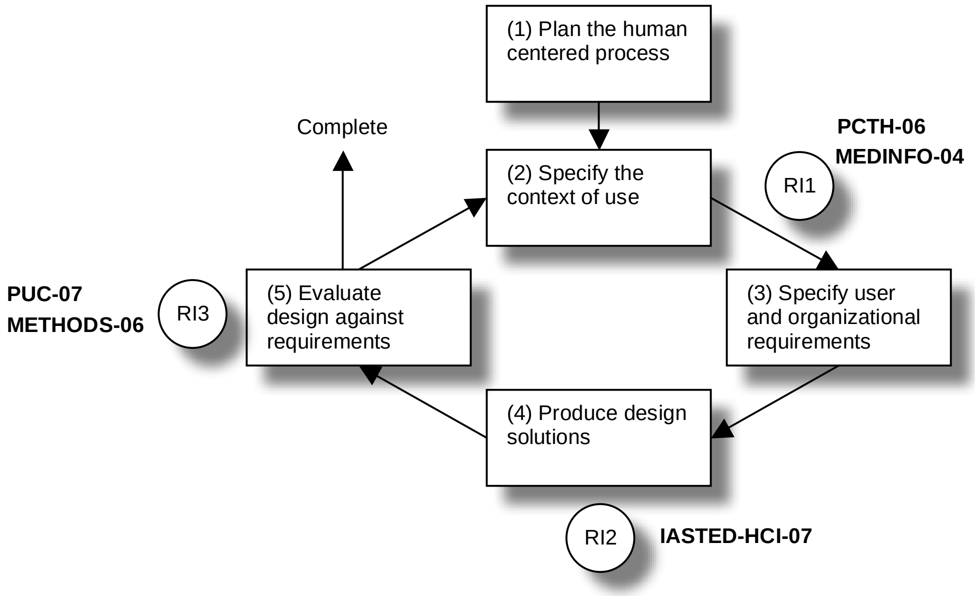

Fig. 14 Relation between papers, research questions, and activities of user-centered design.

7.1 Analysis phase

The first research issue (RI1), presented in Sect. 2.2, is primarily relevant for the analysis phase of user-centered design. Its aim was:

To identify requirements for digital media and navigation models supporting access to medical information at point of care.

As previously pointed out, this research issue corresponds to the subjects addressed respectively in PCTH-06 and MEDINFO-04.

7.1.1 Contributions of the proposed context model

The contribution of MEDINFO-04, in terms of informing the analysis phase of a user-centered design process for ubiquitous computing at point of care, is primarily in form of the context model the paper proposes (Fig. 9). It defines a *conceptual model* presenting an idealized view of how context-based navigation in patient related information can be structured.

A conceptual model, as defined by Johnson and Henderson [61] is a high-level description of how a system is organized and operates (Norman [62] refers to such models as *design models*). Johnson and Henderson (op. cit) point out that conceptual models should ideally help users develop accurate mental models of the system. Accordingly, it specifies the major design *metaphors* and *analogies*, the *concepts* that the system exposes to the user (data objects users create and manipulate, their attributes, and operations users can perform on them), the relationship between the concepts, and the mappings between the concepts and the task-domain the system is designed to support. These components, as implicated by the proposed model, can be specified as follows:

- Metaphors/analogies: A context pathway is analogous to a timeline of events relative to a specific hospital worker or patient.
- Concepts: The primary concepts are the *context pathways* of patients and hospital workers. Caregivers should be able to navigate along these, and perform relevant operations such as hide irrelevant information, switch between context-pathways, and search for specific contexts (see Sect. 5.1).
- Relationships: In the model, the context-pathways of a patient and a hospital worker join and overlap to reflect which patient the care related activities performed by the hospital worker concerns.
- Mappings: Each timeline or context-pathway corresponds to the history of events (taking place inside the patient information system or in the real world) relevant for a specific patient or hospital worker.

7.1.2 Implications of the proposed context model

The context model presented in MEDINFO-04 can be considered complementary to interaction models constructed with the visual formalism presented and evaluated in IASTED–HCI-07. While the formalism described in the latter paper can help describe physical aspects of context relevant for context-aware interaction at point of care, the model proposed in former paper can help describe changes in the context of hospital workers (and patients) over time. As such, the context-pathways can act as a visual tool for describing the temporality that characterizes clinical work and as a metaphor for context-based information navigation.

7.1.3 Contributions of the media-affordance analysis

The media-affordance analysis described in PCTH-06 draws attention to the way clinical work depends closely on the quality of paper as a medium. The analysis shows that none of the digital media that were studied can satisfy all the affordances and constraints associated with the paper-based medication chart, and at the same time provide computer technology functionalities (e.g., hyperlinks and dynamic update) in an immediate fashion.

Identifying the affordances paper-based patient charts offer during prescription and medication (see PCTH-06) is important for understanding the use context which digital counterparts need to accommodate. At the same time, many of the paper-based affordances can inform user requirements for digital patient charts.

7.1.4 Implications of the media-affordance analysis

The media-affordance analysis conducted as part of PCTH-06 is relevant in terms of how the affordances associated with paper can help inform and inspire design of pervasive and ubiquitous computing solutions for clinical use. During an analysis phase, many of the affordances offered by paper-based media used at point of care (e.g., paper-based medication charts) can be considered important design requirements that must be understood and reinterpreted in terms of computer interfaces, devices, and representations in order to replace paper with digital media. This can include restoring functionalities such as the physical flexibility of paper, identifying appropriate physical tokens that can represent handover of tasks and responsibility in the same manner as paper does, and restoring the possibility to link information to physical places or objects. As such, affordances offered paper-based medication charts can act as a helpful design inspiration for developers of point-of-care systems.

7.2 Design phase

The contribution of the current thesis in terms of informing the design phase of user-centered design of UbiComp solutions for clinical use has primarily come out of the research work addressing RI2. The aim of RI2 was:

to develop a practically applicable modeling technique that allows location-aware and token-based interactive systems to be described from the perspective of users in situ, with a focus on the physicality of the use situations.

7.2.1 Contributions of the visual formalism for modeling location and token-based interaction

The visual formalism described and evaluated in IASTED–HCI-07 forms the main result of the research activities conducted in relation to RI2.

The representations constructed with the formalism can be regarded as *physical models* in the sense that they describe the physical reality of the human-computer interaction. This stands in contrast to conventional computer system modeling formalisms (e.g., UML class and object diagrams), which principally intended to describe how computer systems work on the "inside"—their primary concern is how information is represented in, and exchanged between software objects. Hence, this class of models can be considered *system models*. Even UML use-case diagrams and formal HCI methods like task analysis, although they aim to represent a user-perspective, are to a large extent blind to the physicality that characterizes UbiComp systems.

An early version of the formalism appears in PUC-07, where it is used to identify appropriate sensor-based interaction techniques for point-of-care access to medical information. The resulting interaction models illustrate how the formalism can be made relevant for design of UbiComp in clinical settings.

7.2.2 Implications of the visual formalism for modeling location and token-based interaction

De facto modeling formalisms, such as UML, tend to remove physical features of the real-world system that is modeled. How users can provide computer input, properties of the devices and tools, and colocation between interaction elements are examples of aspects that are not easily communicated through system models. This can be viewed to indicate the need for physical models when designing UbiComp solutions.

As the formalism described in IASTED–HCI-07 implies, one way of accommodating such design aspects is to think visually. The proposed formalism allows interaction to be described sequentially across storyboard-like views (frames) using building blocks that represent elements that are part of the physical user interface of UbiComp systems. As previously pointed out, the expert group evaluation of the formalism suggested that it is intuitive to use in practical modeling tasks, and that the implicit user perspective promotes reflection and discussion on design solutions.

Offering a novel way of modeling UbiComp systems, the proposed formalism can be complementary to conventional system modeling formalisms.

7.3 Evaluation phase

The last research issue (RI3), as presented in Sect. 2.2, was:

to identify the main usability issues of interaction techniques and services associated with ubiquitous computing, in relation to clinical point-of-care situations.

This research issue has been addressed mainly in PUC-07 and METHODS-06.

7.3.1 Contributions

The contributions of the current work with regard to RI3 and the evaluation phase of user-centered design concern:

- User-perceived evaluation criteria for ubiquitous computing at point of care.
- Physical design considerations for point-of-care solutions.
- Lessons learned from experimenting with sensor-based interaction techniques for accessing medical information at point of care.

Identified user-perceived evaluation criteria

PUC-07 identifies a lack of consensus concerning evaluation criteria for UbiComp systems. Instead of deciding on a set of criteria beforehand, participants were encouraged to comment freely on the usability of the systems being tested. These qualitative data was used to identify relevant usability issues or areas of concern (*required user attention*, *predictability of system behavior*, and *integration with work situation*).

The three emerging areas of concern were found to be largely covered by or in strong agreement with earlier taxonomies (e.g., [63, 64]. Some of the specific findings, such as the need for perceivable interface elements (for predictable system behavior), are reflected in Norman’s early design principles described in POET [22]. Hence, the novelty of the findings does not so much lie in identified evaluation criteria as such, but is rather related to the end user perspective that they reflect, and the method by which they were identified.

Existing comparative studies of interaction techniques (e.g., [65]) have focused on finding statistically significant differences between the techniques with respect to user performance and task completion metrics. These experiments rely on quantifiable predefined evaluation criteria. As such, they represent comparative summative evaluations of the ‘‘products’’ being tested.

A compromising strategy could be to identify a priori the set of metrics that one believes are most relevant. The inherent danger in such an approach is that one can make wrong selections, and end up focusing on aspects that are irrelevant or of less significance for the application area. The difficulties of identifying relevant evaluation criteria a priori motivated an inductive approach, resulting mainly in qualitative data. The identified areas of concern are a result of a formative evaluation.

The concept of usability (cf. ISO 9241-11) is related to the subjective user experience of using a specific tool in a particular environment for a precise purpose.

As such, identifying aspects of the systems that the hospital workers see as relevant in immediate work situations can therefore be considered a step towards a guiding framework for user-centered evaluations of UbiComp solutions for hospitals.

Evaluating physical aspects of design

As the usability evaluation described in PUC-07, METHODS-06, and the media-affordance analysis described in PCTH-06 indicates, physical design aspects are highly relevant for supporting seamless interaction with point-of-care systems.

The evaluated interaction techniques presented in PUC-07 all utilized basic contextual features such as information about the test participants' current physical position or the references contained in the tokens (corresponding to patient ID or hospital worker ID). Thus, from the users' perspective the various interaction techniques are distinguishable through different physical configurations of input and output devices. Feedback from the hospital workers participating in the evaluation suggested that the perceived usability of the different techniques to a large extent is influenced by the way these configurations accommodate the changing physical and social conditions of the work situation. Often, this was found to be related to subtle qualities of the designs, such as the possibility to share screen content with patients, or hide it from casual bystanders. Generally, these are examples of aspects that are not captured with summative evaluations performed in conventional usability laboratories.

As pointed out earlier, the participants' arguments for giving the interaction technique combining location-based input with fixed output medium (i.e., bedside terminal) a high rating were related to the ability to have both hands free, to have little focus away from the patient, and the perceived positive effect of sharing the screen with the patient.

The evaluation of the location-based virtual notes (METHODS-06) revealed that utilizing the physical environments of hospital wards for mediating informal digital information between personnel, has a promising potential in terms of improving timeliness of information and reducing reliance on hospital workers' memory. At the same time, the evaluation helped identify potential usability challenges that elements of interaction (e.g., virtual notes), which are not "user-visible" may cause. As discussed in the paper, this requires designers to consider alternative means for notifying users about the presence of virtual notes, and to reflect on which physical objects that are most suited for posting of notes in order to promote timely access.

PCTH-06 identified a set of key affordances (e.g. physical flexibility, visibility) of the paper-based patient chart, which were directly related to its physical properties.

Similar observations concerning the relevance of physical design aspects have also been made in recent studies addressing usability of mobile IT solutions for hospital workers. In a usability evaluation comparing PDAs and tablet PCs as media for nursing documentation, Rodríguez et al. [66] found that the small size and weight of PDA were one of the factors that made these devices more attractive from nurses' point of view (in spite of small screen size and display resolution).

Physical and ergonomic design considerations have also been relevant for the evolution of conventional desktop interaction, as we know it today. The desktop computer mouse is an example of a design which has been developed to accommodate physical and ergonomic aspects of interaction [67]. In contrast to ubiquitous computing, however, conventional desktop computing is far more standardized both in terms of possible input and output devices and the physical settings.

The empirical findings described in PUC-07 and METHODS-06, and the media-affordance analysis described in PCTH-06, can be viewed to indicate that development of *usable* UbiComp solutions for clinical point-of-care situations require designers to pay careful attention to the physical design aspects.

Sensor-based interaction techniques put into practice

The lessons learned from experimenting with sensor-based interaction techniques for accessing medical information at point of care primarily concern the use of location-based sensor technologies. In order to appear consistent from a user's point of view, a location-based interaction technique should trigger the same computer system response each time a user is located at a specific point in space. This principle is in many ways in line with the usability heuristics proposed by Nielsen [68]. To achieve consistency Nielsen (op. cit) argues that "*Users should not have to wonder whether different words, situations, or actions mean the same thing*." The usability evaluations (PUC-07 and METHODS-06) showed that in practice, it can be challenging to conform to this principle when system behavior is based on input implicitly provided by users, i.e., through user actions that are consequential rather than intentional. Increasing the number of sensors in the physical environment can be one possible way of increasing precision of measurement. This issue, however, is ultimately a question of cost to benefit.

7.3.2 Implications for the evaluation phase

The implications of the current study in terms of informing user-centered evaluation of ubiquitous computing at point of care are essentially related requirements for *how* such designs should be evaluated.

Realism and prototype fidelity

The identified evaluation criteria, physical design considerations for integration with ongoing work situations, and the lessons learned from doing practical evaluation of sensor-based interaction techniques in point-of-care situations illustrate how ubiquitous computing requires careful study of the use setting, hospital personnel, and their tasks.

During post-test interviews participants often related the tests to their own work experiences and commented on the usability of the prototypes as if tests had been conducted in their own work environment. This can be seen as an indication of an acceptable level of experienced realism in the experimental setup. At the same time, it illustrates how simple UbiComp prototypes can act as a catalyst for reflection and inspiration for participants. This, again, emphasizes the value of doing practical usability testing of candidate solutions in realistic environments.

The results of the usability experiments suggest that early evaluations of physical user interfaces of UbiComp designs can be performed without considering the details of graphical interfaces. Using graphical user interfaces with low fidelity can help participants to maintain focus and provide feedback on the physical interface of the evaluated system.

The need for evaluating multiple solutions

The concept of usability is central to ISO 13407. Developing designs that are usable from an end-user perspective is a key motivation for adopting a user-centered design process when developing UbiComp for hospitals. At an overall level, this study has identified that the usability of ubiquitous computing designs applied in point-of-care situations often is dictated by the physical and social characteristics of the immediate use situation. This has been recognized in three of the papers contained in Part II:

1) The evaluation of the interaction techniques in PUC-07 showed that there are potential advantages as well as disadvantages associated with each technique. Small changes in the use context can decide if these advantages or disadvantages present themselves to hospital workers at point of care.
2) The usability evaluation of the *location-based virtual notes* in METHODS-06 revealed that test participants found it useful to have variants of the same service for different purposes. This included using it both for personal use (i.e., as a personal reminder service) and for interpersonal use, and having the option of using both implicit (location-based) and explicit information retrieval.
3) The media affordance analysis conducted in PCTH-06 revealed that none of the digital candidates were able to restore all the affordances and constraints associated with paper-based patient charts, and simultaneously provide computer technology functionalities in an immediate fashion. In order to accommodate different aspects of care situations, hospital workers need a set of various I/O devices to choose from.

The difficulties of approximating at design time the factors that influence the usability in an immediate use situation can be viewed as an incentive for designers of point-of-care systems to consider a number of potential solutions. Notably, both the ISO 13407 model and the *usability engineering lifecycle* that Nielsen [25] proposed (Fig. 3, p. 9) suggest that for any given design problem, multiple solution should be considered.

The findings above suggest that with regard to UbiComp for clinical use there might be a set of complementary solutions that are appropriate for different instances of a use situation. This again, can be considered a motivation for designers to implement multiple solutions if feasible.

The design process suggested above is to a large extent in accordance with Chalmers' and MacColl's concept concerning *seamful integration of tools* [69]. Drawing on Weiser's talks [70, 71], Chalmers and MacColl point out the danger of reducing the heterogeneity that characterizes ubiquitous computing. Specifically, they warn against "*loosing the richness of each tool*" by forcing users to conform to one primary tool, or reducing or simplifying tools in order to obtain compatibility. In many ways, this corresponds to what Ebling [72] describes as a "swiss army knife" approach. The result of such an approach could be a tool that may do many things, but none of them well. Seamless interaction, as argued by Chalmers and MacColl (op cit.), can be achieved through seamful integration of tools, i.e., having tools that maintain their individual characteristics but at the same time work together as a whole.

The current study has shown that different interaction techniques, I/O devices, and variants of a location-based information exchange service have individual characteristics that can fulfill immediate requirements that can present themselves at point of care.

8 Summary and conclusions

8.1 Summary of contributions

The current thesis has addressed a set of issues relevant for user-centered design of ubiquitous computing for point-of-care situations. The contribution of the research, and its relevance for the analysis, design, and evaluation phases of such a process, is summarized below:

- *Analysis phase* (specification of use context and requirements, cf. steps 2-3 in Fig. 14).
    - The thesis has proposed a design model presenting an idealized view of how context-based navigation in clinical information can be conceptualized (see MEDINFO-04). Using the proceedings of event in the information system and in the real world as a basis, the model presents a novel way for representing context shifts in clinical care.
    - The conducted research has identified how paper as information medium offers affordances (and constraints) that are central for clinical information work (see PCTH-06). Many of these functionalities can be considered requirements that need to be restored as paper-based media are replaced by digital media. The current work has also shown how some of the affordances offered by paper-based patient charts can be restored through techniques and principles associated with ubiquitous computing.

- *Design phase* (production of design solutions, cf. step 4 in Fig. 14).
  The current work has proposed and evaluated a visual formalism intended guide thinking about accommodating the physical reality of human computer interaction in UbiComp environments (see IASTED–HCI-07).

- *Evaluation phase* (Evaluation of design against requirements, cf. step 5 in Fig 14).
  A significant part of the study has concentrated on evaluating sensor-based interaction techniques and services in point of care settings (see PUC-07 and METHODS-06). This has helped identify:
    - User-perceived evaluation criteria for location and token-based interaction at point of care.
    - The need for conducting evaluations that address physical aspects of design solutions, and how well they adapt to changing work conditions at point of care (the design phase of the next iteration should reflect lessons learned from such evaluations).
    - Practical considerations with regard to the sensor precision, when input is implicitly provided in the background of the user's attention.
    - The fruitfulness of designing and evaluating multiple UbiComp solutions for one particular problem or task.

8.2 Conclusion

In terms of informing the various activities and phases of a user-centered design process for ubiquitous computing in hospitals and at point of care, the conducted research has been no more than preliminary. It has nevertheless provided some relevant insights. In particular, the current work has emphasized that designing for point-of-care usability requires designers to consider the implications that clinicians' mobility, physical work activities, and event-driven work environment raise throughout all the activities that comprise user-centered design.

The need for appropriate conceptual models

The analysis phase and particularly specification of use context raise the need for appropriate conceptual models that can act as basis for further design. Clinical information work is distributed both in space and time, and personnel need to switch from one context to another with minimal delay and effort. These are aspects that need to be reflected in the conceptual model of the system. The proposed context model allows changes occurring inside and "outside" (i.e., in the real word) the computer system to be captured within the same representation, and in the form of a structured timeline relevant for a specific user. The empirical grounding of the model, however, requires further research.

Media matters

Regarding specification of user requirements (analysis phase) for point-of-care systems, many of the media affordances associated with paper-based medication charts can give input to this. Especially, affordances related to the physical properties of paper need to be restored and reinterpreted if digital media is to replace paper. The current investigation suggests that this cannot be done with one computerized medium alone, but that a set of interactive media with different physical properties is required.

Physical user interfaces require physical models

Designing solutions that support context-aware interaction at point of care requires modeling techniques that help guide thinking about accommodating physical and situational aspects of interaction. The proposed and evaluated visual formalism can be considered a modeling tool for describing physical representations of UbiComp systems. As such, the formalism offers a different perspective on UbiComp systems than the one conventional system models can provide.

Evaluating the total user experience

With relevance to the evaluation phase, the conducted research has indicated how changing physical and social conditions at point of care affect usability of UbiComp designs supporting access to medical information. It has shown that practical usability experiments, with simplified candidate solutions and end users performing simulated tasks in realistic settings, encourage participants to relate the testing to their own work experiences, and comment on the usability of the prototypes as if the testing was conducted in their own work environment. Simple UbiComp prototypes can act as a vehicle for reflection for participants during such experiments.

This study has shown that testing simplified prototypes in realistic settings can contribute to identify subtle factors in the use context that can affect the usability of the UbiComp designs. Most critically, the current work has emphasized that for UbiComp the total user experience does not separate physical aspects of a system (hardware and physical flexibility) from software aspects. Evaluations of UbiComp designs for point-of-care use should therefore focus on hospital workers' movements in and computer interaction in physical space.

The benefit of multiple alternative solutions
Lastly, the current study has shown that approximating at design time the contextual factors that affect the usability in an immediate situation is difficult. This can be viewed as an incentive for designers of point-of-care systems to consider a number of complementary solutions, and if feasible implement the set of solutions that is found most appropriate.

The research results of the current study can be viewed as a platform for future research on UbiComp technology applied in hospital work.

8.3 Directions for future research

Some directions for further investigations include:

- The prototypes used in the practical usability experiments (PUC-07, METHODS-06) have only shown "mock-ups" or simplified graphical representations of medical information. Future assessment will require coupling to real medical information systems.
- The current research has predominantly focused on single-user scenarios. Hospital work however is highly collaborative. The evaluated interaction techniques (PUC-07) and the location-based information exchange service (METHODS-06) need also to be tested in multi-user scenarios.
- A more comprehensive evaluation of the formalism described in MEDINFO-04 can be achieved by assessing its applicability in an ongoing research and development project.
- The context model suggested in MEDINFO-04, which facilitates context-based navigation, can be implemented and tested with functional prototypes applied in context-aware environments.

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Part II

Papers

Context in Care—
Requirements for Mobile Context-Aware Patient Charts

(MEDINFO-04)

Context in Care – Requirements for Mobile Context-Aware Patient Charts

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Abstract

The hospital ward is a highly dynamic work environment, in which healthcare personnel rapidly switch from one task to another. The process is partly planned, and partly driven by events and interrupts.

A mobile electronic patient chart (MEPC) will be an important tool for supporting order entry and accessing, communicating, and recording clinical information. The users need to switch from one context to another with minimal delay and effort. Context-awareness, the ability to sense relevant situational information, can allow the user interface of the MEPC to adapt to various situations.

In this paper, we present a future scenario from the coronary care unit. This scenario is analyzed and discussed in order to develop requirements for design methods, context models, and system properties of the MEPC.

Keywords

Handheld computers; Point-of-care systems; Computerized Patient Records; Context-Awareness; User-computer interface.

Introduction

Emerging information technology is steadily making patient information more widely accessible to healthcare personnel through the migration of paper based records to computerized patient records (CPR). Due to advances in mobile technology, the CPR can now be accessed by healthcare personnel in a wide variety of situations through mobile terminals. The work activities in the wards can be described as a combination of formal procedures, informal practices, and mobility. Despite the number of clinical situations and tasks handheld computers can be used in, most mobile clinical information systems remain unaware of the situation of use, and do not adapt. Navigating such systems, seeking relevant information, can be a process involving multiple and complex steps.

One answer to these challenges suggests imbuing mobile patient chart systems with *context-awareness* – the ability to sense situational information relevant to the interaction between a user and an application [1]. Most research activity within context-aware computing has focused on sensing and making use of situational information such as *location*, *time*, *identity* and *action* for automating services. This paper argues that more abstract notions of context, e.g. task, roles, and plans, will have to be considered when designing mobile context-aware tools for healthcare personnel in clinical settings.

This paper explores some aspects of the rich "context space" of clinical ward activities, and gives an example of mobile clinical computing that is different from most other mobile application areas. Our contribution is a set of requirements for context models, design methods, and system properties.

To illustrate some of the situations where a future *context-aware* mobile electronic patient chart (MEPC) [2] could be useful, we first present a scenario from the Coronary Care Unit (CCU). After presenting the background and motivation of our work, we discuss some aspects of the health care domain and why designing mobile context-aware tools supporting ward activities is challenging. The example scenario is then decomposed and analyzed in terms of contextual triggers and context information. We discuss requirements for realizing the context-aware MEPC based on the decomposition and analysis of the example scenario.

Example: Coronary care scenario

It is in the afternoon. Dr. Davis is on call and has just arrived at the ward.

Almost immediately she is called upon by nurse Neil (using the MEPC) who asks about patient Palmer's medication – more specifically he asks about the patient's dose of Warfarin (an anticoagulant).

After checking the status of the patient, Dr. Davis is about to enter the medication dose, but then she is called to patient Adams who has had a ventricular tachycardia. She has to go there immediately, leaving the medication of patient Palmer unfinished.

As she is approaching patient Adams, vital information is read into Dr. Davis' earplug from the speech synthesis unit in the MEPC.

While Dr. Davis is working on patient Adams, the alarm goes as patient Taylor gets cardiac arrest. Since Dr. Davis is not available, Dr. Osborn from another ward gets a message on his MEPC. After Dr. Davis is finished treating patient Adams and has arrived in the office, the MEPC automatically displays the unfinished task of patient Palmer's medication.

Figure 1 -

Background and Motivation

The concept of context has been paid much attention to within research on human-computer interaction. Context information can be used to interpret explicit acts, making communication much more efficient [3]. With the introduction of Ubiquitous computing, the term "context-aware computing" has become a key issue in creating user friendly and efficient systems for computing devices of all sizes and for all purposes. The work of Dey, Abowd and Salber [1] represents in many ways the state-of-art within frameworks for context-aware application development. Additionally, several contributors have supplemented, or focused on aspects of context-awareness not covered in this framework.

Context has been considered as both a representational problem, and a problem concerning interaction [4]. These two separate perspectives on context draw on theories usually associated with positivism and phenomenology respectively. We want to point out that the presented requirements assume that these perspectives are different, and not mutually exclusive.

Recently, context-awareness has also been addressed within the field of health informatics. One example is the Clinical Application Suite (CAS), a multi-tasking software architecture that facilitates the development, deployment, and use of advanced clinical information management applications where the user's context is preserved [5, 6]. The CAS was a precursor for the Health Level Seven (HL7) Context Management Standard specified by the Clinical Context Object Workgroup (CCOW) [7]. The standard describes an architecture (Context Management Architecture – CMA) that serves as a basis for synchronizing and coordinating clinical applications so that they automatically follow the user's context [8]. The CCOW Technical Committee has developed and ratified several versions of the standard, each version adding new specifications. One important area under discussion for a future version of the standard is CCOW/CMA for handhelds, which introduces new and challenging issues.

The report "The Clinical Headings Version 3: Context and Clinical Records" produced by NHS Information Authority has proposed a set of terms to capture the context in which clinical terms are set [9]. These terms were known as the 'context of care' and consist of four groups of terms: Attribution terms, heading terms, status terms, and link terms. The report also describes a formal model of the context terms.

An example of a context-aware clinical system is a prototype of a medicine administration system that has been developed by Centre of Pervasive Computing in Denmark and tested at Aarhus County Hospital [10]. The system is able to register and react upon certain changes of context, such as the presence of a nurse holding a medicine tray for a patient.

The challenges related to design of context-aware tools are multi-faceted. Lack of suitable models and methods, technological issues related to building a context-aware infrastructure, and interaction issues [1] represent challenges which have to be met. Below, we present important issues directly related to design of context-aware tools for clinical settings. These issues have been a central motivation for this paper.

Health care is knowledge intensive: Health care is to a large extent knowledge-driven. Knowledge is seldom an explicit attribute such as location, time or identity. Tacit knowledge, for example, may be difficult to describe and utilize. Intuition is an example of implicit knowledge which plays an important role in healthcare personnel's decision making [11].

Context-aware applications generally make use of explicit and static information, where the detected context information triggers one specific service. These assumptions are not valid for applications supporting health care. It is easy to get context-information wrong, even when building sophisticated context-aware applications. This could have fatal consequences in clinical settings.

Ward activities are situation-driven: Ward activities are also driven by sudden and often unforeseen events, such as the incidents referred to in our example scenario. Determining in advance which services to trigger under which circumstances may prove difficult. Even discovering the right triggers for a specified event are sometimes a non-trivial matter.

Aspects of context in care

Dey, Salber and Abowd defines context as: "Any information that can be used to characterize the situation of an entity, where an entity is a person, place, or object that is considered relevant to the interaction between a user and an application, identity and state of people, groups and computational and physical objects" [1]. In our setting, the entity the chart user. The context also includes information about relevant record content, reminders, orders, or requests.

Formally, we can look at a context as a database of facts that hold in a certain situation. It is this database that a context- aware system will sense, and react on. The database can contain facts about the physical world, user actions, and other information. For any context, there exists a hierarchy of more general contexts, each with less (specific) information. Guha and McCarthy [12] have described various context models according to the lifting (generalization) rules that they employ. For now, we only need a basic understanding of more and less general contexts.

A context will obviously change as things happen in the information system and the real world. Such a proceeding of contexts will be called a context pathway. However, we also want the user to change the context explicitly, i.e. navigate by contexts. For example, the user should be able to:

- Change to a partly specified context that has occurred.
- Spool backwards through a pathway of contexts.
- Jump to any, partly specified, preprogrammed, or explicitly chosen context.
- Send a reminder to someone with an attached context.
- Predetermined reminders can be regarded as part of the context.
- Regard choosing a patient in a menu as conceptually the same as walking close to the patient.
- Block certain (disturbing, irrelevant) context elements.
- Search for contexts.

- Switch to the context of another role at a specific point in time.
- Switch between contexts, stack them, and assign priority.

Explaining the example scenario

Returning to our ward example, figure 1 depicts the context pathways of different persons in the ward. We assume that all healthcare personnel have MEPCs connected to an advanced clinical information system with plans, reminders, and sufficiently rich record representation. The narrative underneath gives an outline of context changes, events, notifications, and the behavior of the user interface for Dr. Davis' MEPC.

<u>1. Time, identification, location</u>

It is in the afternoon. Dr. Davis is on call and has just arrived at the ward.

As she arrives at the ward, she logs onto the information system. Based on current time (start of the shift), her role and identity, and the location (CCU), the display of the MEPC shows a list of patients that are new to Dr. Davis, new test and examination results for already known patients, and other relevant information.

<u>2. Notification, identification, context change</u>

Almost immediately she is called upon by nurse Neil who asks about patient Palmer's medication – more specifically he asks about the patient's dose of Warfarine (an anticoagulant).

The query from the nurse is in form of a standard request for an assessment. The context of the assessment consists of an identification of patient Palmer, and the relevant part of his medication plan for Warfarine that nurse Neil was studying on the MEPC when sending the request. Dr. Davis is notified by the request (being part of her context). She accepts it, and immediately changes to the context that nurse Neil had when sending the request. Dr. Davis' former context is pushed, and can be resumed at a later stage. Her actual decision with regard to Warfarin depends on several factors, for instance, the diagnosis of the patient (e.g. atrial fibrillation or deep vein thrombosis), if the patient is set up for surgery, and new blood test results. All this information is automatically shown on her MEPC.

<u>3. Notification, identification and context change</u>

After checking the status of the patient, Dr. Davis is about to enter the medication dose, but then she is called to patient Adams who has had a ventricular tachycardia. She has to go there immediately, leaving the medication of patient Palmer unfinished.

Yet another predefined request is issued by monitoring equipment, or by nurse Neil. This time the request only refers to the context of the apparatus, i.e. physical location. The MEPC may find out who the patient is from background knowledge.

<u>4. Task, identification</u>

As she is approaching patient Adams, vital information is read into Dr. Davis' earplug from the speech synthesis unit in the MEPC.

Dr. Davis accepts the request and the MEPC switches context appropriately. If the patient is known, new or relevant information may be displayed or read through her earplug. Along with the alarm, important patient information (e.g. name, location, date of birth) and the tachycardia procedure is shown.

<u>5. Task – role filtering of request</u>

While Dr. Davis is working on patient Adams, the alarm goes as patient Taylor gets cardiac arrest. Since Dr. Davis is not available, Dr. Osborn from another ward gets a message on his MEPC.

The system detects that Dr. Davis is busy helping patient Palmer. The request is routed to Dr. Osborn from another ward, who is the nearest available doctor on call.

<u>6. History reminder, location</u>

After Dr. Davis is finished treating patient Adams and has arrived in the office, the MEPC automatically displays the unfinished task of patient Palmer's medication.

Dr. Davis gets a reminder about the unfinished medication task.

Based on the decomposition of our scenario, the proposed underlying MEPC system seems to fit its purpose in terms of ward activity supportive context functions. Communication between healthcare personnel is supported (messaging), as well as coordination of activity (alarm routing, reminder function). In other words, from a system perspective the proposed MEPC system might seem to meet all the requirements we have discussed.

Requirements for context models

In addition to the basic features of a context model from the user's point of view, some global system requirements must be met in order to have a sound and safe system:

1. All important information must be visible in some context within reasonable time.
2. Reminders must be captured and handled within a reasonable time limit: The higher priority, the shorter delay.

Requirements for design

In order to discover which context information is essential for healthcare personnel, and in what way the specific context information is used, deep insight into daily ward activities is necessary. Design methods which are characterized by a high degree of user involvement, such as user-centered design is therefore appealing. Especially, iterative design where the users take part of all stages, like within the Scandinavian tradition, is a promising alternative within system design [13]. Techniques like role-playing can be used to explore important aspects of mobility and the role mobile electronic tools play when they are introduced in an activity. Such techniques may also prove valuable for designers of mobile context-aware tools in clinical settings, especially during the early phases of requirements gathering.

System properties

The following system functionalities represent the most important considerations to be taken into account when designing mobile context-aware tools for healthcare personnel.

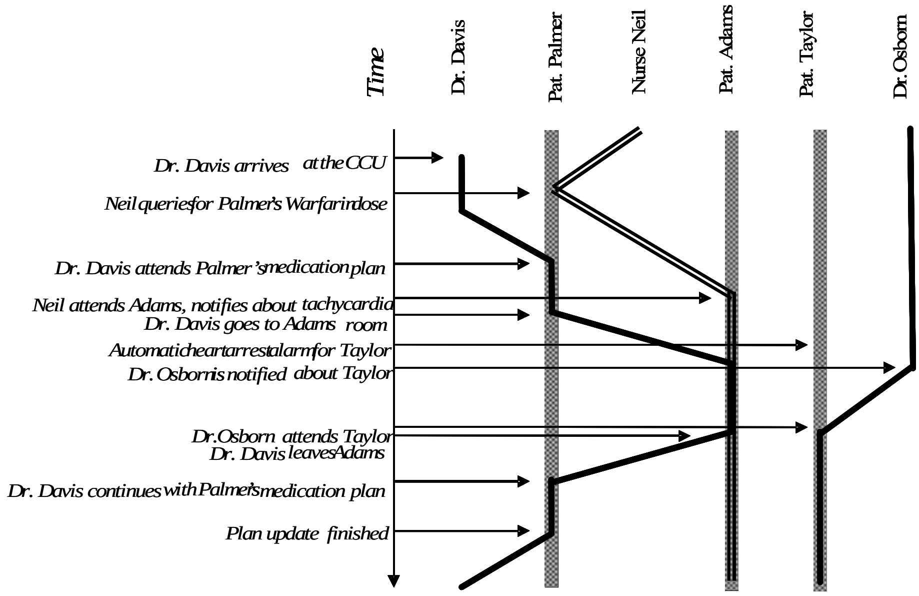

Figure 2 - Context pathways in ward example

1. Caution concerning automatic execution of services

Greenberg [14] suggests that context-aware systems generally should be "fairly conservative in the acts it takes". This principle certainly holds for context-aware tools supporting ward activities. In particular, services the system can perform which directly concern the treatment of the patient should always be confirmed by the authorized healthcare personnel before execution. As a result, the context-aware functions related to a MEPC should focus on supporting *presentation of information* and *attachment of context information for later retrieval* as described in the conceptual framework of Day, Abowd and Salber [1].

2. User control

User control does not simply imply that the user should be notified, or that he should have to confirm every action the system intends to take. Rather, for seamless integration with day-to-day ward activities only potentially "risky" actions should have to be explicitly confirmed by the user. An additional aspect of user control is giving healthcare personnel the option of configuring both the user interface and context-aware functions of the MEPC.

3. Coordination of perspectives

By giving healthcare personnel the option of configuring the user interface and context-aware functions, there is also potential danger which calls for special attention. Enabling the individual user to put his perspective on "the world", may result in that some context information filtered out by everyone at the same time. Consequently, information concerning a patient may be lost. If every member of a care team, for example, is able to disable all notification regarding a certain patient, the result could obviously be disastrous. An important system property is therefore to support coordination mechanisms guaranteeing that no information remains "unseen" by all healthcare personnel simultaneously.

4. Navigating in context

A MEPC that is aware of its own location, as well as surrounding healthcare personnel, patients, and medical devices allows location-based automatic or user-controlled navigation in the patient chart. This may be supplemented by physical actions like scanning tags on a particular patient.

Tagging of information for later retrieval is a central function for many context-aware devices. Time-stamping information in itself, however, does not make the MEPC more user-friendly. The MEPC should provide means for navigating between different chart contents classified according to episodes of use, for example location, activity, roles, and other context attributes. Important parts of gathering requirements are to discover and classify relevant episodes of use. The MEPC could even allow for healthcare personnel to define their individual classification of episodes.

Conclusion

We have discussed various requirements for realizing a mobile electronic patient chart (MEPC) which can sense and utilize different sorts of context. In order to illustrate the rich "context space" of clinical settings, an example scenario from the Coronary Care Unit was explained and analyzed in terms of context changes, events, notifications, and the behaviour of the MEPC user interface. The analysis points out particular requirements on context models, design, and system properties for the context-aware MEPC. We have elaborated on these requirements to make them usable for designing mobile devices that support healthcare personnel in a user-friendly, efficient and safe way.

Acknowledgments

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Designing Pervasive Computing for Hospitals: Learning from the Media Affordances of Paper-Based Medication Charts

(PCTH-06)

Designing Pervasive Computing for Hospitals: Learning from the Media Affordances of Paper-Based Medication Charts

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***Abstract*—The current article investigates the affordances associated with paper out of the motivation that this can help inform design of pervasive and ubiquitous computing solutions for clinical use. In particular, we will focus on paper-based medication charts, and discuss how these artifacts differ from various digital and context-aware solutions both in terms of media properties and functionalities. Based on a comparison of media, we argue that the affordances offered by the paper-based medication charts are not fully transferable to *one* digital medium, but that a combination of complementary digital media is required.**

***Index Terms*—Affordances, Interaction design, Pervasive computing, Point-of-care systems, User interfaces.**

I. Introduction

PAPER-BASED media still play an essential role in clinical work [1, 2]. While computers have effectively replaced paper and associated routines in many other work settings (e.g. office work), conventional desktop computing has had comparatively less impact on the work processes in daily clinical care. One feasible explanation for this is that hospital wards, in contrast to office settings, are highly mobile working environments, and that stationary desktop computers do not integrate well with hospital work [3]. This can be seen as a key incentive for providing clinicians with means to access medical information at the point of care, e.g. through mobile computer devices and wireless network technology.

While simple medium-portability can be achieved through contemporary handheld computer devices such as mobile phones, PDAs, tablets, etc., recent studies suggest that there are functionalities offered by paper-based media that are not directly transferable to digital media. Bång and Timpka [4] argue that paper-based patient records help form cognitive tools that reduce clinicians' reliance on memory, and support joint attention and collaboration. In an extensive study of non-digital media and the role they play in clinical coordination, Bardram and Bossen [2] point out that when physical documents such as work schedules are computerized, most of their natural affordances (e.g. the possibility to take notes on it, erase things, and add post-it notes to it) are lost in the process.

Supporting seamless interaction with digital media in and across everyday clinical situations is a key argument for applying solutions developed for pervasive and ubiquitous computing. Generally, interaction with such systems is to a larger extent physical in the sense that elements of interaction no longer are limited to the virtuality of the screen, but are also physically present in the real world.

For computer-based solutions to successfully replace paper as the primary medium for clinical coordination and information exchange, an understanding of the essential properties and functionalities of paper is required.

In the current article we investigate the affordances associated with paper, and compare paper-based medication charts with selected digital and context-aware alternatives. Our motivation is that we believe this can help inform design of pervasive and ubiquitous computing solutions for clinical use. While paper-based media come with certain natural affordances that are difficult to transfer to digital media, we argue that ubiquitous computing techniques can bring back or preserve some of the affordance associated with paper as hospitals go digital.

In section II relevant background information on the concept of *affordance*, and particularly affordances of paper, is presented. Section III gives examples of key affordances offered by paper-based patient charts. Section IV describes a set of sample designs where context-aware media replace the paper-based medication chart. In section V the various sample solutions are categorized in terms of media properties, and compared with paper-based charts to identify affordances that are transferable. The comparison, and the way the media affordances of paper-based medication charts can inform design of pervasive and ubiquitous computing for hospital work are further discussed in section VI. Lastly, conclusions are drawn in section VII.

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II. Background

A. Affordances and Constraints

A number of CSCW studies (e.g. [5]) have analyzed *the affordances of paper*. The *affordance* concept is a potential source of misunderstanding. In popular user-interface design jargon it is often used to refer to a visual element's ability to communicate its function in the interface. As pointed out by Don Norman [6], the source of this confusion can be found in his use of the term in POET [7]. Similar to Sellen and Harper [5], we will use *affordance* in its original meaning as it was formulated by J.J. Gibson [8]. Gibson invented the term to denote the *relation* between an animal and its environment. It describes what the environment *offers* that organism. It is a relation because it is not a property of the environment *per se*, but a property of the environment for a specific organism. The tree affords climbing for a cat, while for a horse the same tree only affords scratching. Affordances vary not only with species, but also with attributes such as age, skill, and physical ability. For an adult human being, pen and paper affords communication through writing, while this is not an affordance offered by pen and paper for a pre-school child.

Gibson was concerned with perception and action "in the wild". He used *affordances* to refer to perceived affordances, i.e. not to theoretically possible ways for an organism to interact with its environment.

Gibson analyzed the affordances of environments for organisms living in those environments. From this perspective it is meaningless to talk about the affordance of an object, such as a piece of paper, without referring to the environment it is a part of. A piece of paper in an environment without a pen cannot afford writing.

It follows from the above that an analysis of the affordances of an object requires an understanding of its users and its context of use. This understanding cannot be reached solely by studying the object in isolation. It requires observations of actual use and knowledge about the users. In this sense affordances are similar to the concept of *usability* as defined in ISO 9241-11 [9].

In POET [7] Norman used the term *constraint* to refer to factors that limit the possible actions that an object *affords*. He distinguished between different kinds of constraints. *Physical constraints* make certain actions physically impossible. Paper placed in a plastic cover does not allow for annotations. *Cultural constraints* are dictated by conventions and by the dos and do-nots of a social setting. Paper on someone else's office desk does not allow for annotations.

For a specific user in a specific setting, the environment *affords* certain actions limited by certain *constraints*. Gaver [10] and Oshlyansky et al. [11] provide a more detailed analysis of the affordance concept and its relevance to interface design.

B. Literature review

A number of studies have put focus on paper as an analytic resource, with the intention of informing design of new computer technologies. The current review gives by no means a complete overview of relevant studies. Instead, we have made a careful selection of frequently cited work that we view as particularly relevant with regard to design of pervasive and ubiquitous computing solutions supporting hospital work.

1) Paper properties and examples of affordances and constraints

Sellen and Harper [12, p. 200] identify a set of partly interrelated paper properties that directly affects what one can do and what one cannot do with paper. The properties are (quote):

- *A single sheet is light and physically flexible.*
- *It is porous, which means that it is markable (absorbs pigment) and that marks are fixed and spatially invariant with respect to the underlying medium.*
- *It is a tangible, physical object.*
- *Engagement with paper for the purpose of marking or reading is direct and local. In other words, the medium is immediately responsive to executed actions, and interaction depends on physical copresence.*

The following terms can be used to refer to respective paper properties listed above: *Physical flexibility*, *Information-medium inseparability*, *Concreteness*, and *Direct and local engagement*.

These paper properties can provide a wide variety of affordances, but simultaneously imply certain interactional constraints depending on the situation of use. Below, we provide some examples described in relevant literature.

<u>Physical flexibility</u>:
Being light in weight and physically flexible paper affords *ecological flexibility* [12, 13]. This flexibility, or *handability* [14], allows a document to be easily manipulated by hand. For example, paper can easily be moved about, handed over to collocated persons, locally distributed, attached (taped, clipped, stapled, glued) to other documents and physical objects. Luff and Heath [13] view this flexibility as an essential requirement for media supporting collaborative activities.

The little weight and physical flexibility also allows paper to be carried across physical distances, i.e. it is portable.

<u>Information-medium inseparability</u>:
One of the most defining characteristics of paper, vis-à-vis conventional computerized media, is what Harper and Sellen [15] refer to as the *fixedness* of information with respect to its medium. That is, the paper medium and the information it contains are inseparable. This means that information on paper cannot easily be revised, reformatted or put into other documents. To quickly and effortlessly replicate the information on a paper document, one therefore has to use a scanner or a photocopying machine.

Loosing or destroying the medium means that the contained information is lost as well.

Sellen and Harper [12, p. 201] point out that a positive effect associated with the inseparability of information and medium is that it allows multiple people working on the same document to leave their own distinctive persistent marks on it. This way, both the history of changes and who made which marks become visibly traceable.

Concreteness:
Paper-based practices typically imply storing, retrieval, and delivery of paper. Bardram and Bossen [14] describe routines regarding the movement of paper-based medical records between archives and a hospital ward, and how the records are transported around the ward by means of a trolley. In [12, p. 201] it is noted that the physical efforts involved in storing, retrieval, and delivery of paper often increase with the amount of documents involved.

On the positive side, paper can act as a physical cue or reminder. Bång and Timpka [4] address the role paper-based patient records play with regard to cooperation between clinicians in a hospital emergency room. They argue that paper-based patient records form a shared public display, and act as a common visual representation of status and work in progress. It is also argued that this reduces clinicians' reliance on memory.

Paper can also act as physical tokens that represent hand-over of tasks and responsibility. Bardram and Bossen [2] describe how the leader of the nursing team writes down new tasks, prescriptions, and examinations on post-it notes, which are put on a whiteboard in a team room, or directly handed over to a hospital worker who is taking care of the relevant patient.

In [12, p. 201] it is also argued that the process of handling over a paper from one person to another can promote social interaction and discussion.

Direct and local engagement:
One of the obvious shortcomings of paper documents in a mobile working environment is that they cannot be accessed or distributed from a remote location. Sellen and Harper [12, p. 202], however, note that aspects such as short response time and no interoperability problems allow for immediate and reliable interaction. In a study of document use by anesthetists, Harper et al. [16] argue that paper also allows for *non-disruptive* use. For example, a person can take notes relatively easily during an ongoing dialog without taking too much of his or her attention away. This non-disruptiveness can in many ways be considered related to the flexible information capture that paper supports. Free text annotations can easily be added directly to a paper document.

Because paper is portable and can be manipulated by hand, one can make the contained information unavailable to others (e.g. by carrying away the paper, or by turning it facedown hiding contained information from collocated persons). As such, a person can limit both the medium's accessibility and visibility. As pointed out in [1] and [14] limited accessibility is of special relevance with regard to the paper-based medical record of which there can only exist one copy.

2) A summary of identified affordances and constraints of paper

Based on the studies described above, we have identified a number of partly interrelated affordances and constraints that apply to paper as an information medium. These are summarized in Table I.

III. Case study: Paper-based medication charts

In order to compare a paper-based practice taking place in clinical hospitals, with potential digital and context-aware solutions, we have chosen to focus on the use of patient medication charts (see Fig. 1) in relation to drug prescription and administration. Drug prescription and administration are common scenarios in hospital wards, occurring on a regular basis each day. Table II gives a sequential description of typical events that are related to these scenarios. The narration is based on a previous field study described in [17].

A typical prescription and medication scenario involves a physician, a nurse and a number of patients. In the morning meeting of this particular day the physician reviews the current prescription, does not change anything, and confirms by signing for the day.

After the meeting, the morning administration round starts. The nurse takes the medication charts for his patients

TABLE I
AFFORDANCES AND CONSTRAINTS OF PAPER

Property	Affordances	Constraints
Physical flexibility	*Handability*: Paper provides ecological flexibility, which means that it can easily be manipulated by hand. *Portability*: Paper can be carried around to support mobile work.	
Information-medium inseparability	*Visible history of changes*: Modifications and idiomatic remarks become easily traceable.	*Uniqueness*: Information and medium can only be at one location at a time. If the medium is destroyed or lost, so is the contained information.
Concreteness	*Physical cue*: Paper can act as a physical cue or reminder. *Physical token of responsibility*: Paper can act as a physical token representing hand-over of tasks and responsibility. *Social interaction*: Since paper must be physically delivered, it can promote social interaction. *Shared display*: Paper can be a common physical focus for co-located people.	*Physical effort*: Paper needs to be physically stored, retrieved and delivered.
Direct and local engagement	*Immediacy and reliability*: Response time is instant, and there are no interoperability issues. *Non-disruptiveness*: Paper allows for non-disruptive use (e.g. during conversation), and flexible information capture (e.g. free text annotations).	*Local interaction*: Paper cannot be accessed or distributed from a remote location. *Exclusive access and visibility*: If a person carries with him a paper, this affects both the accessibility to the contained information for others and their visibility of the medium.

Table I: Summary of common affordances and constraints associated with paper.

TABLE II
REGULAR PRESCRIPTION AND ADMINISTRATION WITH PAPER-BASED MEDICATION CHART

Context	Actors-Acts
Morning meeting.	The physician in charge reviews the current prescription. The prescription plan is changed directly on the chart, or left unchanged. The physician confirms the review, and possible changes, by signing the day's plan in the appropriate box.
After meeting. Morning administration.	A nurse physically carries the charts for his patients to the drug room. The drug trolley is fetched.
In drug room.	The nurse selects and fills a drawer in the drug trolley for each patient. The nurse confirms that the drugs are ready for administration by countersigning the chart. The drug inventory of the room is also updated and signed for each patient and each drug.
By patient bed. The patient is awake and alert.	The nurse collects this round's drugs in a small container and leaves it by the bed. The nurse signs the appropriate box in the chart that drugs have been administered.

Table II: Sequential description of the events that take place during drug preparation and administration.

and brings a drug trolley to the drug room. At the drug room, the nurse selects and fills a drug trolley drawer for each patient. To confirm that the drugs have been made ready for administration in the trolley, the nurse countersigns each patient's daily medication plan. The drug inventory of the room is also updated and signed. The nurse then moves the trolley to the first patient bed. The nurse collects this round's drugs in a small container and leaves them by the bed. For each patient, the nurse signs that drugs have been administered.

The prescription/administration-scenario described above and in Table II exemplifies many of the paper affordances and constraints summarized in Table I:

- *Handability*, *portability* and *immediacy* are essential qualities of the paper during administration: This activity is mobile in nature, takes place in locations where information work is secondary to a main activity of patient treatment or manual work involving drugs and other remedies.
- *Visible history of changes* and *uniqueness* are important in combination because it gives clues to the prescribing physician and administrating nurses, the necessary context for understanding and validating the current prescription. Aspects like authorship, responsibility, history of change, and context of decision become immediately understandable (albeit in a compact and cryptic fashion) with a paper chart (cf. Fig. 1).
- The chart is a *visible* and *physical token of responsibility* during the entire administration process, and gives *exclusive access* to the information, preventing changes during administration and possible risks associated with multiple administrations of the same dose.
- In the morning meeting, the medication chart acts as a vehicle for *social interaction* as it is passed around the table, and is a physical focus of common attention, i.e. a *shared display*.
- During the drug administration, *non-disruptiveness* allows focus on the critical interaction with the patient.

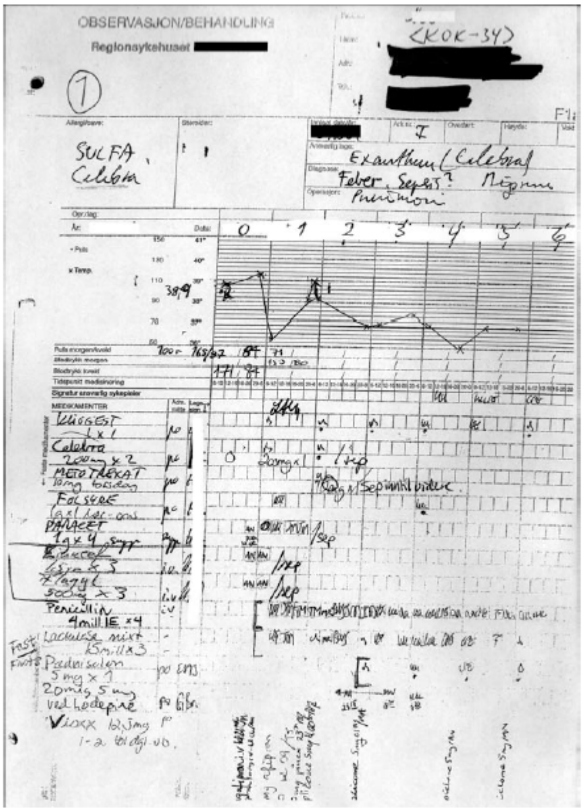

Fig. 1: Paper-based medication chart (patient sensitive information has been edited out).

IV. REPLACING THE PAPER-BASED MEDICATION CHART WITH CONTEXT-AWARE MEDIA

Section III gave examples of important qualities of the paper-based chart. A key incentive for computerizing routines that are paper-based is that digital technologies can compensate for many of the limitations associated with paper. Some essential functionalities that digital technologies can offer include:

- Dynamic modification and updating of content.
- Storing of, and access to large amounts of (digital) information.
- Remote concurrent interaction.
- Fast searching.
- Hyperlinks to related information.

In this section we will briefly describe a set of ubiquitous computing designs that serve to give examples of how the paper-based medication chart can be computerized. The various designs differ in terms of the extent to which they provide hospital workers with digital media that have paper chart-like properties.

A. Location and token-based solutions

In a related study, described in detail in [18], Dahl and Svanæs compare different interaction techniques that can provide hospital workers with access to relevant medical information at the point of care (corresponding to event 4 in Table II). The comparison is based on practical usability testing, and discusses usability issues emerging from a set of experiments. For the current purpose, we will only focus on the implementations of the various techniques, and regard them as candidate solutions that can replace the paper-based medication chart.

Each candidate solution that was tested as part of the study provided access to simplified electronic medication charts by combining location or token-based input with fixed or mobile output devices. Location-based input was estimated using radio positioning sensors and positioning tags that were attached to the test participants. Credit card sized barcode cards acted as tokens. Bedside terminals (with 19” touch-sensitive screens for signing) provided fixed output, while PDAs provided mobile output. Barcode scanners were attached to the PDAs and the fixed bedside terminals when interaction techniques that involved the use of tokens (barcode cards) were tested.

Specifically, the components described above allowed for the following combinations:

1. User location / mobile device (UL/MD): User location indicates which medication chart that is selected. The selected chart is presented on the hospital worker’s PDA when he or she enters a predefined area (i.e. a virtual zone) surrounding a patient bed. The technique is illustrated in Fig. 2.
2. User location / fixed device (UL/FD): Similar to the previous technique, except that output is provided on a terminal (with touch-sensitive screen) fixed to the respective patient’s bed (see Fig. 3).
3. Fixed token / mobile device (FT/MD): By means of a barcode reader on the PDA the hospital worker can scan barcode cards attached to each patient bed. Each barcode refers a specific electronic medication chart. Output is given on the PDA. An implementation of this variant is shown in Fig. 4.
4. Mobile token / fixed device (MT/FD): The hospital worker carries tokens that can be read by barcode scanners attached the bedside terminals used for output (see Fig. 5). This opens up for two different configurations:
   a. The hospital worker carries one token that identifies him or her. Each bedside terminal is associated with one specific patient, and can only provide access to that patient’s medication chart.
   b. The hospital worker carries a set of tokens that each exclusively identifies a patient. Each bedside terminal can provide access to any patient medication chart provided that the user carries the correct token.

If we use paper-based medication charts as an analogy, interaction techniques 1-3 and 4b is comparable to a condition where the paper charts remain located by their associated patients at all times. Technique 4b, on the other hand, draws more directly on the metaphor of paper-based medication charts in the sense that users (i.e. hospital workers) must carry with them physical representations of the medical information.

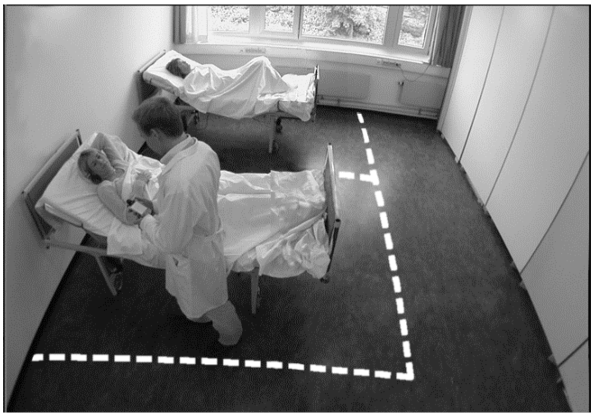

Fig. 2: User location / mobile device: When the hospital worker enters the virtual zone marked by the white lines (invisible to the hospital worker) the associated electronic medication chart is automatically presented on his PDA.

Fig. 3: User location / fixed device: The fixed bedside terminal responds as the hospital worker enters the virtual zone, and presents the associated electronic medication chart.

Fig. 4: Fixed token / mobile device: A patient's electronic medication chart is retrieved by scanning the fixed token attached to his or her bed.

Fig. 5. Mobile token / fixed device: Scanning a mobile barcode card with the reader attached to the fixed display retrieves the electronic medication chart.

The various candidate solutions described above can be thought of as ways to physically standardize a number of work processes or low-level operations that are associated with the handling and moving of paper-based charts. Operations like search, retrieval, and transportation of medication charts, can all be considered integrated in one physical action – Either approaching a patient (location-based solutions), or scanning a token indicating a medication chart (token-based solutions).

B. *Digitally augmented paper*

One approach to partly recreate the flexibility of paper is to provide hospital workers with digital media that have paper-like properties, such as a device with little weight that allows to be carried around, and that supports stylus-based input (e.g. PDA-based solutions). In work described by Bång et al. [19], this approach has been taken even further. It focuses on the applicability of digital paper interfaces for clinical use. Medical data that clinicians enter on special paper forms using digital pens are electronically captured by an underlying computer system. This approach is in many ways more in line with Weiser's vision of ubiquitous computing [20] in the sense that the users do not interact directly with a computer as such, but indirectly via an artifact with embedded computational resources. Instead of changing current paper-based routines, this approach attempts to seamlessly integrate computer technology that is invisible in use.

V. Properties and Affordances of Context-Aware Media Compared with Conventional Digital and Paper-Based Media

As described in section II, the affordances and constraints associated with paper in various situations are related to certain properties that define the medium. Based on the work of Sellen and Harper, we pointed out that some of the key properties of paper are its (1) physical flexibility, (2) the inseparability of the information and the medium, (3) its concreteness, and (4) the direct and local engagement that paper requires. At an overall level, these are aspects that say something about (1) the type of interaction the medium allows for, (2) characteristics of the interface of the medium, (3) how the medium presents itself to the user (i.e. its appearance), and (4) preconditions for access to the information content.

Based on such a classification, Table III shows a comparison of paper-based and conventional digital solutions, and the context-aware alternatives discussed in section IV. Conventional digital solutions include classic client-server solutions that allow medical information to be accessed from a remote desktop computer.

We also consider mobile computing devices with wireless access to digital networks to be in the category of conventional electronic solutions. Although handheld devices like PDA and tablets potentially can allow hospital workers to access digital medical information "anywhere" and "anytime", the underlying interaction model of these devices are largely similar to that of traditional desktop computing. This is in the sense that both conventional desktop computers and handhelds remain unaware of events occurring in their surrounding environment.

A. *Media characteristics*

Below, we explain the media classification shown in Table III in further detail.

1) *Appearance*

Interactive systems present themselves to users in different ways. As opposed to conventional systems, context-aware systems can include both physical and virtual components in addition to conventional computing devices. In the location and token-based alternatives described above, tagged users and non-digital tokens (barcode cards) formed physical components of interaction.

While physical components such as tokens (and token readers) are immediately visible to users, a virtual zone has to be explicitly marked to be directly observable. Even if

TABLE III
MEDIA CHARACTERISTICS

Medium / Feature	Paper-based medication chart	Stationary (desktop) computing	Mobile Computing	User location/ mobile device	User location/ fixed device	Fixed token/ mobile device	Mobile token/fixed device (a)	Mobile token/fixed device (b)	Digitally augmented paper chart
Appearance	Paper	Desktop computer (with keyboard, mouse, and display)	Mobile computing device (e.g. PDA or tablet PC)	Mobile computing device and physical area around patient bed.	Fixed bedside terminal and physical area around patient bed.	Mobile computing device and token fixed to patient bed	Fixed bedside terminal and mobile hospital worker ID token	Fixed bedside terminal and patient ID token	Paper (Special paper form)
Interface(s)	Physical (i.e. the paper)	Virtual	Virtual	Physical and virtual	Physical and virtual	Physical and virtual	Physical and virtual	Physical and virtual	Primarily physical
Interaction (Input)	Paper (direct input with e.g. pen)	Only through GUI (fixed)	Only through GUI (mobile)	User location (mobile) Screen touch for signing	User location (mobile) Screen touch for signing	Fixed token Screen touch for signing	Mobile token Screen touch for signing	Mobile token Screen touch for signing	Paper (input with digital pen)
Interaction (Output)	Paper (Direct output)	GUI (large)	GUI (small)	GUI (small)	GUI (large)	GUI (small)	GUI (large)	GUI (large)	Paper (Direct output or via GUI)
Preconditions for access to information content	The user and the chart must be co-located. Charts must be physically transported around to various points of care.	The user must locate a stationary desktop PC, log in, and navigate to the correct chart.	The user must carry a mobile computing device, and navigate to the correct chart.	The user must be co-located with the patient (i.e. within the virtual zone surrounding the patient bed). A valid positioning tag is required.	The user must be co-located with the patient (i.e. within the virtual zone surrounding the patient bed). A valid positioning tag is required.	The user must carry a mobile device that can read the token attached to the patients bed.	The user must be co-located with the patient (i.e. his/her bed), and must carry a personal ID token.	The user must carry the correct Patient ID token, and locate a terminal that can read it.	The user must carry the augmented charts with him to provide input at various points of care. Verified input is remotely accessible.

Table III: Classification of medium properties of context-aware media, conventional digital media, and paper-based media.

not visibly marked, areas with location detection are still perceivable to users through interaction, and hence part of the manifestation of the medium.

2) Interfaces

Tokens and physical areas with location detection allow users to interact through what can be thought of as the physical interface of an interactive system. Such a physical interface may co-exist with a conventional screen-based (virtual) interface to the same digital information.

Paper-based media has only a physical interface inseparable from the medium, and can therefore provide only one view or perspective on the contained information.

3) Interaction

Different interfaces support different kinds of interaction. Input for paper is pen-based, and output is direct. Typical input devices for desktop computers include mouse and keyboard, and output is typically mediated via the GUI. The PDAs and bedside terminals used in the location and token-based candidate solutions allowed for touch-based input (by stylus or hand) for signing.

For the location and token-based solutions, certain input (medication chart selection) could also be mediated via fixed or mobile physical tokens or via the users' physical position.

4) Preconditions for access to information content

As previously noted, to interact with paper one must be physically close to it (reading), or in direct contact (writing). This is a consequence of the information-medium inseparability that characterizes paper-based media.

Electronic information, on the other hand, can be accessed remotely, but can only be mediated via computer devices. Pascoe [21] metaphorically describes computers as electronic *lenses* that allow us to see digital information.

In addition to having a computer device that can mediate digital information, users might also need specific *access rights* to read or modify the information. To access a specific electronic medication chart by means of the described location and token-based solutions requires the hospital workers to carry a valid token or radio positioning tag.

B. Media affordances

Because different digital and context-aware media have different properties (appearances, interfaces, interaction-styles, and preconditions for access to information content), the extent to which affordances and constraints of paper are transferable to these media varies. Table IV shows whether affordances and constraints relevant to paper-based medication charts (see section III) are maintained across various digital media. The comparison should not be considered definitive, as it depends on the perspective that is taken. Some particular medium-affordance relationships have been further explained below.

Handability:

Although mobile computing devices like PDAs have paper-like properties, these media do not provide the same flexibility as paper, e.g. in terms of handover, local distribution, and ease of attachments.

TABLE IV
COMPARISON OF MEDIA AFFORDANCES AND CONSTRAINTS

		Medium								
		Paper-based med. chart	Stationary (desktop) computing	Mobile Computing	User location/ mobile device	User location/ fixed device	Fixed token/ mobile device	Mobile token/fixed device (a)	Mobile token/fixed device (b)	Digitally augmented paper chart
Affordance	Handability	✔	–	–	–	–	–	–	–	✔
	Portability	✔	–	✔	✔	–	✔	–	–	✔
	Visible history of changes	✔	–	–	–	–	–	–	–	✔
	Physical cue/ token of responsibility	✔	–	–	–	–	–	–	✔	✔
	Shared display	✔	–	–	–	✔	–	✔	✔	✔
	Promotes social interaction	✔	–	–	–	–	–	–	–	–
	Immediacy and reliability	✔	–	–	–	–	–	–	–	(✔)
	Non-disruptiveness	✔	–	–	✔	✔	✔	✔	✔	✔
Constraint	Uniqueness	✔	–	–	–	–	–	–	–	–
	Physical effort	✔	✔	–	–	–	–	–	–	(✔)
	Local interaction	✔	–	–	–	–	–	–	–	–
	Exclusive access/visibility	✔	–	–	✔	✔	✔	✔	✔	–

Table IV: Indicative overview of paper affordances and constraints that are transferable across various digital media.

Portability:
Portability is supported by designs where users can carry with them the interface to the information.

Physical cuing and token of responsibility:
MT/FD b (patient ID tokens) and digitally augmented paper charts are the only alternatives where each electronic medication chart has a corresponding physical representation that hospital workers can carry with them.

Shared display:
Fixed bedside terminals can act as a shared display between caregiver and patient, and possibly between co-located caregivers. The small screens of conventional mobile computing devices make them less suitable for this purpose.

Promotes social interaction:
Paper-based charts promote social interaction because they require physical handover. Digital information, on the other hand, can be accessed remotely.

Immediacy and reliability:
Digitally augmented paper charts give instant response only to the immediate user. Response from input to computerized devices depends on software and hardware design.

The location and token-based designs rely on the precision and quality of the positioning sensors and token readers.

Non-disruptiveness:
The location and token-based designs can be considered non-disruptive with regard to the drug administration activity. This is in the sense that they do not require the hospital worker to take his or her attention away from the care situation to find the relevant medication chart.

Physical effort:
Accessing digital medication charts through stationary desktop computers implies that a caregiver has to walk over to a computer each time related information is needed.

Similarly to ordinary paper charts, digitally augmented charts must be carried around to the various points of care. This, however, is only required to provide input.

Local interaction:
Digitally augmented paper charts necessitate local interaction to be handled. Input that has been verified, however, can be accessed remotely.

Exclusive access/visibility:
Tokens and augmented spaces that surround the patient beds can potentially act as physical access keys to digital medication charts.

From Table IV we see that many of the more subtle affordances that paper offer such as handability, promotion of social interaction, and physical cuing and indications of responsibility are not provided by most of the digital candidate solutions. For example, of the location and token-based variants, only MT/FD b (hospital worker with patient ID tokens) is capable of restoring the physical token abilities of paper in some sense.

It is first and foremost the aspect of non-disruptiveness that the context-aware solutions are capable of restoring.

Augmented paper solutions are closest to recreate affordances and limitations of paper, but does not directly offer functionalities associated with computerized media, e.g. the possibility to remotely access information, navigate by hyperlinks to related material, and dynamic update of information content.

VI. Discussion

As pointed out in the background section, paper-based media come with rich interaction capabilities. Conventional digital media is far from providing the same interactional flexibility. This flexibility has in many ways contributed to turn paper into a truly ubiquitous technology for hospital personnel.. In this section we will discuss how designers of ubiquitous and pervasive health care systems can learn from the strengths and weaknesses of the paper chart.

A. Changing media and preserving affordances

If we compare the paper-based chart with the location and token-based designs described in section IV we find that the various alternatives can be very different in terms of media characteristics (see Table III). Yet, all alternatives can support point-of-care access to medical information in their own distinctive way. This illustrates that different media do not need to have identical properties to offer the same functionality. For example, in UL/FD it is the interface, and not a physical medium as such, that supports mobile hospital workers at the point of care.

However, replacing one medium with a medium that has dissimilar properties, can limit functionality in other situations of use. The person who carries a paper may prevent a collocated person from seeing the information content, but this control is partly lost when information is visualized on the fixed screen display of a bedside terminal.

The above suggests that the extent to which digital media for medication charts should have paper-like properties cannot be decided upon without taking into account the various situations the chart will be used in.

B. Dedicated media for dedicated purposes

While physical aspects such as the handability and portability of the paper-based medication charts can be essential in some clinical situations, the same physicality can pose limitations in other circumstances, e.g. when the medication charts have to be retrieved, stored, or carried around. This can be viewed as an argument for providing hospital workers not with *one* medium to be used in all situations, but with a set of dedicated media or interfaces tailored for specific purposes. For example, paper or even augmented paper can be an appropriate medium during a pre-rounds conference where the medication chart is an essential part of the social interaction between the participants. During the ward rounds and administration of medicine, however, a location-based solution combined with fixed bedside terminals could be more appropriate. This solution eliminates the need to carry the medication charts between patients (preventing fellow colleagues from access) and also gives the hospital worker the ability to physically interact with the patients without having to bother with a portable device.

On other occasions, it may be useful for clinicians to access medication charts for patients when either patient or clinician is outside the ward. In such situations, a mobile computing device with remote access to electronic medication charts, or a patient ID token that can be scanned at the nearest terminal, could be convenient.

The examples given above illustrate that the affordance concept is highly conditional, and that affordances offered by a medium in one situation might actually limit interaction in other situations and vice versa.

C. Restoring implicit access control

While paper-based charts come with an implicit access control (the one who carries a chart controls its access), this type of control needs to be implemented in conventional electronic computer systems. The context-aware designs can to a certain extent restore this implicit access control. To retrieve an electronic chart, the hospital worker has to be physically close to a patient to provide valid location data input (UL/MD and UL/FD). The same co-presence is also required to scan tokens fixed to the patient bed (FT/MD) or tokens that identify the user (MT/FD a). Physical tokens that identify patients can also provide implicit access control, if there only exist one token per patient (MT/FD b). Location and token-based access control must be included in other policies for access control.

D. The PDA-as-document metaphor

Many of the functionalities that we associate with paper are not directly provided by the medium as such, but through various paper-related tools, e.g. pens, paper clips, staplers, folders, sticky notes, etc. There is a whole “industry” around paper that provides tools with functionalities that contributes to the interactional flexibility of paper.

Mobile computing devices do not have similar digital counterparts to the paper supplies mentioned above. For example, there are no globally accessible digital services that are equivalent to sticky notes in the sense that one is allowed to link digital information to physical objects (further discussed below). As long as such services are unavailable, one may question the appropriateness of applying a document metaphor when paper-based medication charts are computerized.

We suggest that in order to replace paper-based media with digital and context-aware media there is also a need for digital counterparts or equivalents of common paper supplies.

E. Paper supplies as design inspiration – An example

In a related study [22], we explore how computerized interpersonal information can be mediated through the physical environment of hospital wards. The study focuses on a communication service (*location-based virtual notes*) that allows hospital workers to link short digital messages to relevant physical locations (e.g. by a patient bed), so that fellow hospital workers can pick them up later when entering such a location. An extended service might even allow users to link electronic messages to physical artifacts. The type of service described above can in many ways be regarded as a digital counterpart to paper-based sticky notes.

VII. Summary and Conclusions

The current work has investigated affordances of paper motivated by the challenges of designing pervasive and ubiquitous computing solutions for the hospital ward. In particular, it has focused on the role paper-based medical charts play in drug preparation and administration. We have described a set of ubiquitous computing designs in which context-aware media have replaced current paper-based solutions.

The context-aware media have been compared to paper-based charts and conventional digital media to identify how they are different. The extent to which the context-aware media offer affordances that are similar to those associated with paper has also been discussed.

The current work allows us to draw the following conclusions:

- Firstly, we have shown that different media have different characteristics that determine which activities they are appropriate for. Media replacing the paper-based medication chart do not need to have paper chart-like properties to afford similar functionalities in a given situation. For example, supporting hospital workers with easy access to medical information can be done both through digital devices that are mobile *per se*, and through fixed computer terminals located at the point of care.
- Secondly, none of the candidate media that have been discussed can satisfy all the affordances and constraints associated with the paper-based medication chart, and at the same time provide computer technology functionalities (e.g. hyperlinks and dynamic update) in an immediate fashion. In particular, the more subtle affordances are lost. Based on this we encourage an approach that combine various media, and that allows the individual hospital worker to choose the medium that he finds most appropriate in a given situation.
- Thirdly, techniques and principles for ubiquitous computing can potentially restore functionalities that are lost when paper-based practices are computerized. This includes bringing back physical tokens of responsibility, implicit access control, and the possibility to link information to physical places or objects.

We have tried to explain how clinical work is intimately dependent upon the qualities of paper as a medium. These qualities must be understood, and reinterpreted in terms of computer interfaces, devices and representations before we can replace paper with digital media in the hospital.

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Toward a Visual Formalism for Modeling Location and Token-Based interaction in Context-Aware Environments

(IASTED–HCI-07)

TOWARD A VISUAL FORMALISM FOR MODELING LOCATION AND TOKEN-BASED INTERACTION IN CONTEXT-AWARE ENVIRONMENTS

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ABSTRACT
This paper introduces a visual formalism for modeling location and token-based user interaction in context-aware environments. As computer technology is embedded into our surrounding environments and interaction is moved into the physicality of the real world, we argue that there is a need for effective methods that allow designers to model systems as they appear from the outside, i.e. the users' perspective. The current formalism can in many ways be considered a compromise between storyboards and UML case diagrams. To assess the applicability of the formalism we conducted a preliminary evaluation with a usability expert group. The evaluation indicated that key features that make the formalism useful from a designer perspective is its relative simplicity, that it allows designers to build explicit models of interaction for various scenarios, and that it encourages discussion and reflection on design solutions.

KEY WORDS
Interaction modeling, Interaction techniques, Pervasive computing, and Ubiquitous computing.

1. Introduction

Interaction with computer technology is no longer limited to the desktop. Mobile computing devices and wireless communication technology make digital information accessible in diverse environments. This can be seen as a major motivation for enabling computer devices and systems to sense and respond to changing contexts of use – a principle often associated with pervasive and ubiquitous computing (UbiComp). As computer information systems are influenced by activities and events taking place in the physical world, human-computer interaction is no longer limited to conventional input and output devices such as mice, keyboards, and stationary displays. In context-aware environments persons, places, and objects in the world also become potential elements of computer interaction [1]. Effectively, the design space of interactive computer systems is expanded.

Despite the interaction possibilities the new design space opens up for, we find that there are few tools available that allow designers to denote aspects of what could be described as the physical interface of context-aware systems. De facto modeling formalisms, such as UML, tend to abstract away physical features of the real-world system that is modeled. For example, how a user provides computer input, properties of the devices and tools, and co-location between interaction elements is not easily described through conventional formalisms. With regard to traditional desktop computer systems such simplifications can be considered purposeful because these systems are left unaware of their physical surroundings. However, as computer and sensor technology merge with our physical environment, there is arguably a need for tools that supports modeling of user interaction with the physical interfaces of these systems.

Motivated by the need for a well-defined, yet flexible, tool that allows designers to conceptualize user interaction with context-aware systems, this paper presents a simple modeling formalism. It has been specifically developed to support modeling of location and token-based interaction.

To assess the applicability of the formalism and the comprehensibility of the associated notation we conducted a preliminary focus group evaluation with three usability experts.

Section 2 describes relevant background material and the motivation behind the current work. In section 3 we point out the most characteristic aspects of the formalism. The modeling components, their formal notation, and interrelationships are presented in section 4, along with sample models. Section 5 gives an overview of the evaluation with the expert group, and section 6 describes the response from the participants. Some reflections on the formalism and the evaluation are given in section 7, while conclusions are drawn in section 8.

2. Background and Motivation

The modeling formalism that we will present and discuss in the current paper is based on previous work that has focused on context-aware technology from a user's perspective. An early version of the applied notation was introduced by Svanæs [2] as a means to explain how users "make sense" of augmented space. A further specification of the notational building blocks can be found in a more recent study [3]. The latter work also provides more extensive modeling examples, and makes use of a clinical drug administration scenario to show how various models can be implemented.

As part of an ongoing research project on electronic patient records[1], we have focused on various forms of mobile and pervasive computer support for clinical hospital workers. In this connection, we have made use of the formalism internally in discussions concerning potential design solutions. The current work presents a first attempt on an external evaluation of the modeling formalism. The motivation behind the formalism is to provide a tool that allows designers to describe the mental model that they want users to adopt.

The value of considering context-aware technology from a user's perspective has been acknowledged in a number of relevant studies (e.g. [4-7]). In recent times, different approaches that put focus on how mobile and context-aware technologies present themselves to users have been investigated. Scenario-based design [8] and role-playing [9] are examples of methods that are intended to help designers capture and understand how contemporary technologies are or can be used in-situ. There are also examples of techniques that allow designers to represent and model the *situatedness* that characterizes interaction with such systems. Storyboards have been used to model conventional graphical user interfaces, and has more recently been proposed as a useful technique for describing physical and situational aspects of interaction [10, 11]. The modeling formalism discussed in this paper is in many ways similar to storyboards in the sense that it allows for sequential visualization of interaction. This principle is also reflected in earlier prototyping tools for location-aware applications such as *Topiary* [12].

3. Characterizing the Formalism

We consider the current formalism to be an alternative that falls between storyboards on one side, and UML use case diagrams on the other, and that it can be complementary to both. To describe its characteristics we have found it useful to classify it along three dimensions: Formal versus informal representation, granularity, and perspective.

[1] The Norwegian EHR Research Centre (http://www.nsep.no)

3.1 Formal vs. Informal Representation

In contrast to conventional computer system modeling formalisms, storyboards typically do not imply the use of a formal notation, and consequently has a lower level of abstraction. Landay and Myers [13] identify the roughness and lack of detail to be essential features of informal representations. This flexibility means that storyboards can be read and understood not only by system designers, but also by other stakeholders (e.g. users). However, by not conforming to a standard notation, storyboards and other informal representations potentially loose many of the advantages associated with modeling formalisms, such as unambiguousness (each notational shape represents the same category of things), seeing immediate similarities between different designs, and re-use of former solutions on new problems. In addition, models constructed by means of standardized modeling formalisms can be used with computerized modeling tools to automatically generate source code.

By adopting a formal visual notation (see section 4) that can be used to create storyboard-like views (frames) of interaction, the current formalism aims to achieve some of the advantages associated with both of the approaches described above.

3.2 Granularity

Granularity refers to the level of detail at which a system can be described. In principle, the formalism allows interaction to be described in terms of physical *presence*, *proximity*, and *touch* (immediate proximity). In its current form the formalism does not handle modeling of more fine-grained forms of interaction, such as twisting and turning of tokens and directional sensing.

3.2 Perspective – Taking a User's Point of View

Rather than modeling an interactive system from a system perspective, or the way software objects interact, the current formalism focuses on how a system ideally should appear from an external view, i.e. the user's perspective. The resulting models can therefore be regarded as metaphors for the physical interface of location and token-based systems.

4. Formalism Description

4.1 Modeling Components, Notation, and Relationships

To describe location and token-based user interaction in context-aware environments we have developed a set of abstract building blocks. The respective notation is shown in Fig. 1. A short description of the various building blocks and how they interrelate is provided below.

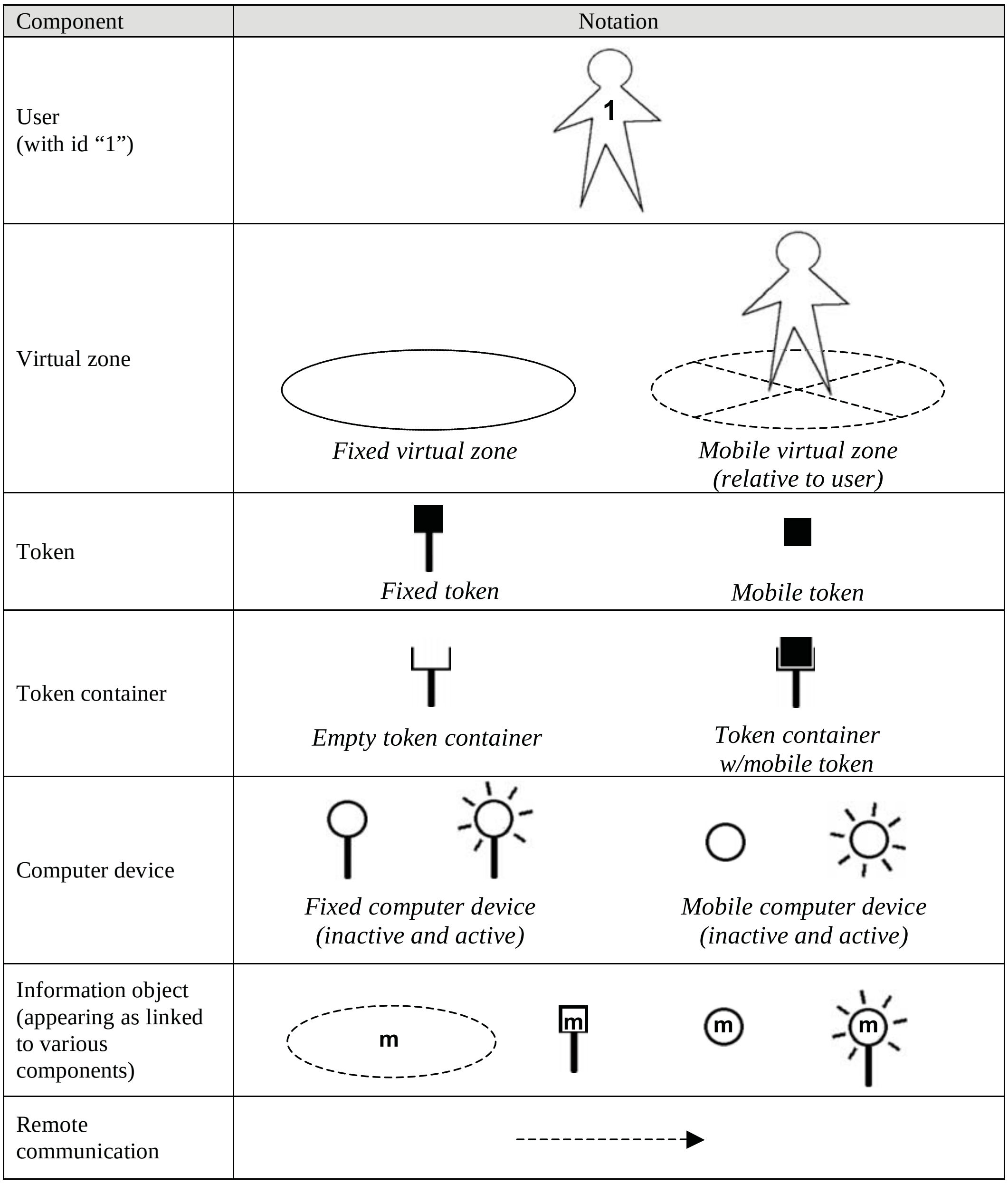

Fig. 1: Notation.

User: Each user is marked with a unique identity (e.g. a number). A user can interact with a computer device by entering or leaving a virtual zone, by scanning a token, or via another computer device. Users can carry one or more mobile tokens or mobile computer devices.

Information object: An information object corresponds to a particular unit of electronic information, such as a web page, an e-mail, an electronic voice message, etc. Users, tokens, virtual zones, and computer devices can contain information objects. To denote information objects we have used bold letters (e.g. "**m**") that are placed inside the symbol of the modeling components they are associated with.

Virtual zone: A virtual zone is a predefined physical area in which presence of users can be detected via sensor technology (e.g. GPS, WLAN positioning, IR, face recognition, etc.) operating in the background. A user entering or leaving a virtual zone can trigger a specific computer device response, i.e. cause an associated information object to be presented (or stop being presented). Location-based interaction is typically considered to be what Buxton [14] refers to as a *background* activity. That is, the triggering of the computer response is consequential, and to a lesser degree the objective of the user.

Virtual zones may be fixed to a particular physical space, or may be relative to the physical position of a user[2]. The physical shape of a virtual zone is implementation specific. To make virtual elements (i.e. virtual zones and remote communication channels) of the system that is modeled easily distinguishable from elements that are physical, the former are drawn with a dashed line while the latter are drawn with a solid line.

Token: Holmquist et al. [15] define a token as a representation of digital information by association or resemblance. We have adopted a similar definition. Accordingly, a token is a physical object that can contain a reference to an information object. In addition we use the term on physical objects that can exclusively identify a user (e.g. a credit card or an access card). A token is considered to be a passive medium. The user has to explicitly provide the contained reference to a computer device (i.e. scan the token with a token reader) in order to get access to the information object. Hence, token-based interaction, as apposed to location-based interaction, typically corresponds to a *foreground* (intentional) activity.

Tokens can be mobile (carried by users) or fixed to a particular location. They can either be digital or non-digital. iButtons[3] are examples of digital tokens, while barcode tags are examples of non-digital tokens. Depending on the actual implementation, the reference that a token contain may be static, or modifiable.

Token container: A token container is a fixed physical object that can receive and hold one or more mobile tokens temporarily or permanent depending on the actual implementation. In the *WebStickers* sytem [16] and *CybSticker* sytem [17] any physical object to which a sticker can be attached can form a token container. For modeling purposes, we consider it sufficient to represent only token containers that are meaningful with regard to the particular scenario that is outlined. While CybStickers remains stuck to the physical objects on which they are placed, WebStickers can be attached to and removed from an object, and potentially reattached to other objects.

Computer device: This building block represents any displays, token readers, wireless network cards, speakers, etc., that are connected, and that users are likely to experience as one unit. Such a unit can be either mobile or fixed to a particular location. A computer device can respond as tokens are scanned, as a user enters or leaves a particular virtual zone, or as other computer devices are physically proximate. This can change the current state of a computer device (1) from inactive (default) to active, (2) from active to inactive, or (3) from one active state to another. A computer device in an active state presents a given information object to a user. Computer devices can distribute information object to other interaction elements.

Remote communication: This component is used to represent conventional network communication (e.g. WLAN). It is a supplement for describing remote distribution of information objects (e.g. from a remote computer device to a virtual zone or token).

As shown in Fig. 2, all physical interaction elements (users, computer devices, tokens, and virtual zones) can contain information objects. These information objects may be associated with a particular interaction element from a remote location. Fig. 3 illustrates the interrelationship between the interaction elements, as described above.

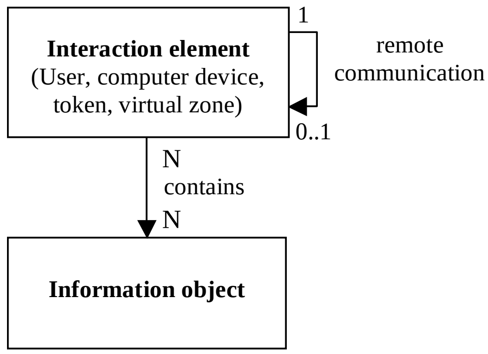

Fig. 2: The semantic relationship between interaction elements and information objects. Each interaction element supports remote communication, and may be associated with an information object from a remote location.

4.2 Examples of Use

The modeling components described above allow us to model a wide variety of interaction techniques. Figs. 4-7 show some simple examples of solution that have been frequently applied within ubiquitous and pervasive computing. These examples can in many ways be considered general UbiComp design patterns that have emerged over the past 10-15 years.

4.3 UbiComp Design Patterns

In Fig. 4 the user's mobile device responds as he or she enters a fixed virtual zone. This is the underlying interaction model of numerous UbiComp prototypes described in relevant literature. Examples include *GUIDE* [18], *HIPS* [19], *Stick-e notes* [20], *Place-its* [21], and the *context-aware pill container* described in [22].

In Fig. 5 the computer response occurs in a fixed device as the user enters a fixed virtual zone. Designs that have made use of this technique include various ambient displays such as *Hello.Wall* [23] and *Mo@i* [24].

Fig. 6 shows the token-based counterpart of the model illustrated in Fig. 4. A fixed token, which has to be explicitly scanned by the user's mobile device, replaces the fixed virtual zone shown in Fig. 4. The WebStickers

[2] Location-aware systems often treat the physical position of a traceable computer device as an indication of the physical position of a user. While such an assumption is practical with respect to modeling purposes, we are aware that this simplification may not hold in many use settings.
[3] http://www.maxim-ic.com/products/ibutton/

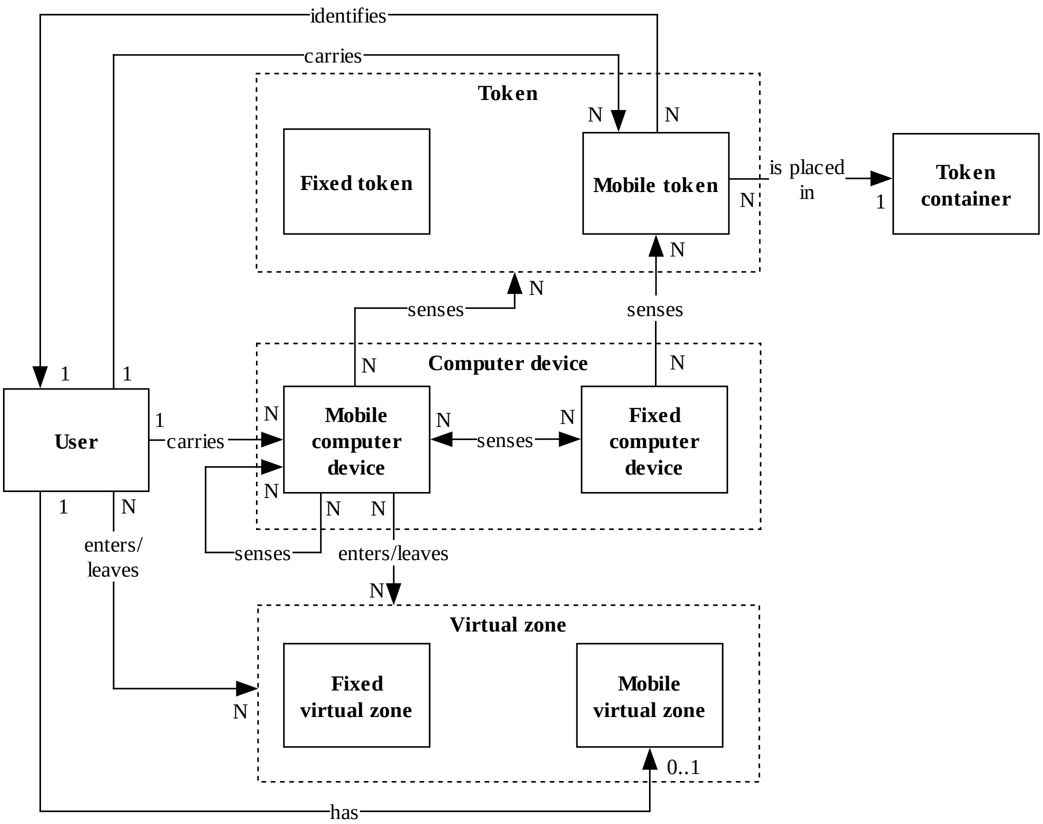

Fig. 3: The semantic relationship between interaction elements.

system mediate (output) information to its users by means of this interaction model. This is also one of the interaction techniques *Cooltown* [25] supports.

In Fig. 7 the token-based counterpart of the model shown in Fig. 5 is illustrated. Here, the user carries a token that must be read by a fixed computer device in order to produce a computer response. A well-known example that implements this interaction model is Durrel Bishop's Marble Answering Machine [26] – The computer device represents the telephone answering machine, and each marble that is associated with an incoming voice message corresponds to a token that is carried by the user. Other examples of UbiComp designs that implement the interaction model shown in Fig. 7 include AmbientROOM – Ishii and Ullmer [27] describe how moving a physical icon or *phicon* (token) into the proximity of an information *sink* (token reader) triggers an ambient display.

An alternative version, involving the same interaction elements, is shown in Fig. 8. Here, the token does not carry an information object, but exclusively identifies the user. Thus, the token can be regarded as an access tool to a specific service provided by the computer device.

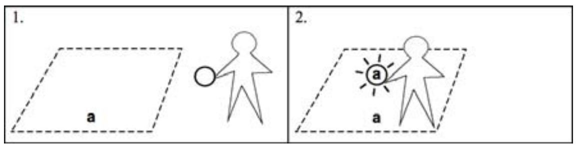

Fig. 4: The user's mobile computer device responds as he or she enters a fixed virtual zone.

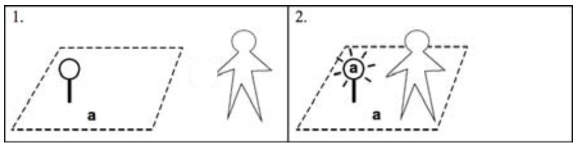

Fig. 5: A fixed computer device responds as a user enters a fixed virtual zone.

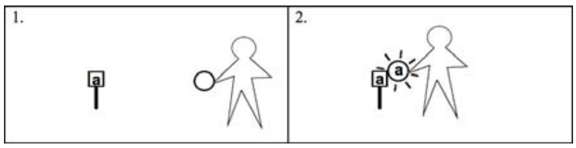

Fig. 6: The user's mobile computer device responds as it reads a fixed token.

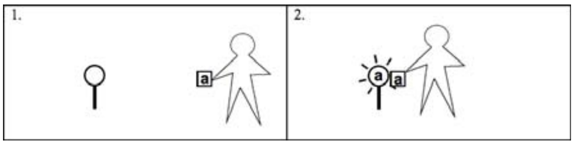

Fig. 7: A fixed computer device responds as it senses the mobile token carried by the user.

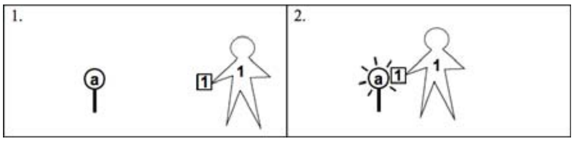

Fig. 8: A fixed computer device responds with a particular service as it senses the token that identifies the user.

To further illustrate interaction techniques that can be expressed using the current formalism, we have included three additional figures (Figs. 9-11). Fig. 9 shows a simplified model of the Hello.Wall system [23]. Fig. 10 and 11 show interaction techniques where various degrees of physical proximity between mobile computer devices trigger response. Fig. 10 shows interaction as it occurs e.g. with *Hummingbirds* [28]. In Fig. 11 an alternative solution where, in contrast to Hummingbirds, it is the immediate physical proximity (i.e. touch) between computer devices that trigger response. This is the underlying interaction model of UbiComp designs such as *iBands* [29].

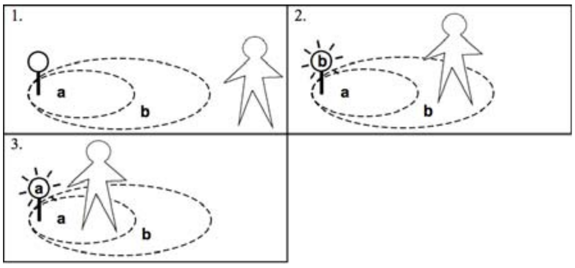

Fig. 9: A fixed computer device responds as the user approaches it.

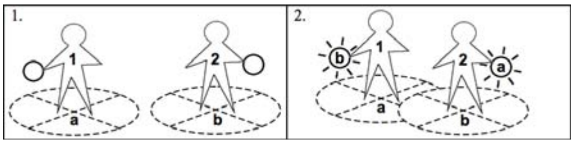

Fig. 10: The users carry mobile computer devices that respond to other proximate users.

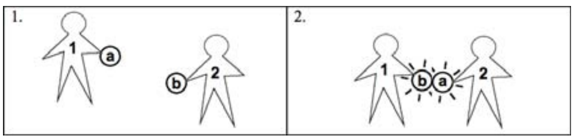

Fig. 11: The users carry mobile computer devices that respond to other computer devices that are immediately proximate.

4.4 Example Scenarios

The current formalism can also be used to build models of particular scenarios. Fig. 12 shows a simplified model of the previously mentioned CybSticker system in a supposed use scenario: (1) A user carrying a CybSticker (token) and his mobile phone approaches e.g. a bench. (2) The user glues the CybSticker to the bench. (3) He then creates an MMS on his mobile phone. (4) The MMS is associated with the Cybsticker by taking a photo of the sticker's unique ID, and sending an MMS to a CybSticker reception number[4]. (5) The user then leaves. (6) Next, a second user walks past the bench, and sees the attached CybSticker. (7) He approaches it, and uses his mobile phone to take a picture of the token. When the picture is sent to the reception number he receives the MMS that was previously associated with the sticker (frame 4).

Fig. 13 illustrates a location-based variant of a similar scenario. In this scenario, however, the information object is distributed from a remote location. We have previously implemented and tested the latter variant in related work [30].

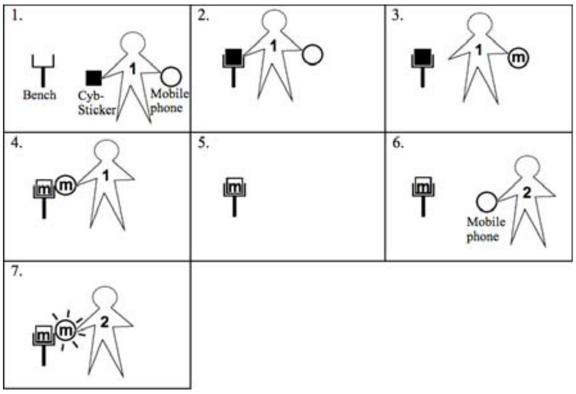

Fig. 12: Interaction with CybStickers in a supposed scenario.

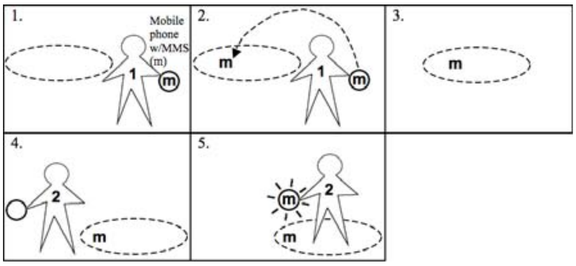

Fig. 13: Location-based variant of scenario shown in Fig. 12.

[4] For simplicity, the process of linking or retrieving an MMS to and from a Cybsticker (Fig. 12, frame 4 and 7) has been represented as one operation. Technically, this consists of two distinct operations. Assuming that a photo of its unique ID has been taken, a CybSticker can be associated with, or checked for information content from a remote location.

5. Expert Group Evaluation

The current section describes the objectives and the structure of the evaluation, and the feedback from the expert group.

5.1 Objectives

As previously pointed out, the overall objective of the expert group evaluation was to assess the current modeling formalism with regard to its applicability to model location and token-based interaction in context-aware environments. More particularly, we wanted to address the following issues:

- The intuitivism and the ease of use of the notational building blocks.
- The extent to which the perspective offered by the formalism can provide valuable insights.
- Potential user groups.

5.2 Structure

Participants

The focus group consisted of three researchers with extensive experience in usability design and testing. Two of the participants had prior experience in modeling ubiquitous or pervasive computing systems, or systems that supported mobile users. For this both participants had used UML.

Data Gathering

The evaluation session was video and audio recorded. Transcriptions from the recordings, the resulting models of three practical modeling exercises, and a questionnaire were used in the subsequent analysis.

Procedure

The overall procedure of the evaluation involved the following steps:

1) *Introduction*: The focus group was informed about the objective of the evaluation, as well as the background of the modeling formalism and the motivation behind it.
2) *Presentation of modeling components, notation and relationships*: The participants were introduced to the various modeling components and their notation. They were also given a short explanation on how the various modeling components interrelate.
3) *Presentation of simple examples*: To give the expert group participants a concrete idea of the modeling semantic, they were presented with the five general modeling examples shown in Figs. 4-8, and the supposed scenario built around the CybSticker concept (Fig. 12).
4) *Modeling exercises*: The participants were given three practical modeling exercises to be solved in collaboration. In the first exercise the users were asked to model a location-based variant of the CybSticker system based on the scenario shown in Fig. 12. In the two subsequent exercises the participants were given the opportunity to model interaction as it occurs in the HummingBird system and with iBands (see Fig. 10 and 11).
5) *Discussion*: This step occurred partly during, and partly after step 4. The intention was to discuss the suggested solutions to the modeling exercises openly with respect to perspective, the appropriateness of the notation, and alternative solutions.
6) *Concluding questionnaire*: To conclude the evaluation session, each participant was given the opportunity to express his first-impression of the applicability and usefulness of the modeling formalism in a short questionnaire (see Fig. 14).

Questionnaire

- *Prior experience*
  Have you previously used formalisms to model ubiquitous/pervasive computing systems or systems that support mobile users? If yes, please list the formalisms you used.
- *Intuitiveness*
  Do you find the modeling components (the notation) intuitive? Are they easy to combine into meaningful models?
- *Usefulness*
  Do you find the formalism useful? Are there aspects that you find particularly positive or negative? Would you consider using the formalism in the future?
- *User groups*
  What do you think the formalism is most appropriate for – To create a common understanding between designers, or between designers and non-professionals (e.g. users, customers, etc.), or both?
- *Suggestions*
  Do you have any suggestions concerning how the current formalism can be modified or expanded to become more appropriate for modeling interaction in context-aware environments? Feel free to sketch your ideas.

Fig. 14: Questionnaire.

6. Results

Many of the aspects and issues that were brought up and discussed during the preliminary evaluation can be considered partly related. To structuralize the feedback from the focus group, however, we have grouped it into the following categories: Intuitiveness and ease of use, utility, user groups, and modifications and extensions.

6.1 Intuitiveness and Ease of Use

At an overall level, the focus group gave a positive response concerning the intuitiveness of the notation and the extent to which it allowed for construction of meaningful models. The practical modeling exercises also indicated that the participants quickly understood how to describe interaction with the respective notation (see Fig. 15).

With some minor exceptions (see section 6.4) the expert group expressed that the icons for the notation were both simple enough for rapid (paper-based) sketching, and expressive enough to allow the distinctive characteristics of the various interaction elements they symbolized to be reflected.

Regarding the extent to which the formalism is suited for practical use, particularly three issues were brought up and discussed during the evaluation. To a certain extent all issues relate to the purpose of the model that is created and its level of abstraction.

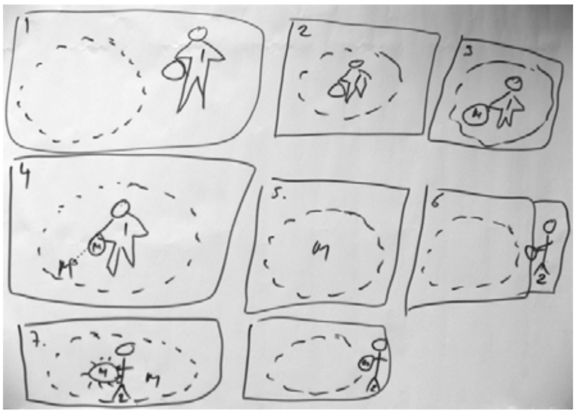

Fig. 15: The expert group's model of the location-based variant of the CybSticker system.

Shorthand Annotations

The first issue had to do with the need for a formal way of referring to the various interaction elements in a model, i.e. a shorthand annotation for users, computer devices, tokens, and virtual zones that are represented. However, it was remarked that such a convention would be helpful primarily from a designer perspective (e.g. such as when translating from one modeling language to another), and that more descriptive labeling probably would make the diagrams more comprehensible for non-professionals.

Frame Detail and Scaling

The second issue that is related to the expert group's perceived practical use of the modeling formalism concerns the level of detail that can or should be represented in one frame. During the presentation of the CybSticker example and during the subsequent exercises this was frequently discussed among the participants. One participant expressed that deciding on the granularity of action in each frame was perhaps the greatest weakness of the formalism, and was uncertain about how well the formalism would scale for complex cases. On the other hand, we also received feedback indicating that idea of outlining particular aspects or subsets of interaction over a series of frames is a practical way to provide detailed system descriptions.

Representation of Implementation Specific Aspects

The last issue concerns the possibility to represent or denote more implementation specific aspects of the model. For example, it was suggested that it would be practical to represent how (i.e. by which technological means) the physical position of a user is detected, quality of service, and possible servers for network communication. Since these aspects were largely considered irrelevant from a user's perspective, it was suggested that they could be described in a supplementary representation (e.g. a sublevel) that could partly present the scenario from designer or system perspective.

6.2 Utility

All participants stated that they found the modeling formalism useful, and that they might possibly use it in future work. The evaluation and the concluding questionnaires indicated various factors that contributed the formalism's usefulness. One such factor was that the formalism allows one to create explicit representations of patterns of interaction as they occur in various scenarios. In addition, it was pointed out that it is well suited for describing combinations of interaction techniques.

We also received feedback indicating that the relative simplicity of the notation added to its usefulness.

Lastly, the practical modeling exercises and statements from the participants indicate that the formalism promotes reflection and encourages discussion on design solutions.

6.3 User Groups

The entire expert group agreed that the formalism, in its current form, is primarily suited for creating a common understanding between interaction designers or between people with experience from ubiquitous and pervasive computing. Depending on the level of abstraction and the complexity of the system that is to be modeled, however, they also saw the possibility that non-professionals (e.g. users) can read and understand models created with the formalism. A precondition for this, as expressed by one of the participant during the evaluation, is that the various interaction elements (users, devices, tokens and virtual zones) that are part of a scenario must be made concrete to the users. As such, the exact physical manifestation of the interaction elements (e.g. the mobile phone, the PDA, the CybSticker, etc.) must be explicitly denoted.

6.4 Modifications and Extensions to the Notation

During the evaluation three modifications and extensions were suggested. Firstly, it was suggested that the icon representing the user could be more similar to the "stickman" icon symbolizing the *actor* in UML. This would make it simpler to draw the user icon by hand.

Secondly, the intuitiveness of the *mobile virtual zone* icon was questioned, but no concrete suggestions on how to improve it were proposed.

Thirdly, a concrete suggestion for formal annotation of interaction elements was given: (1) users: u1..un, (2) tokens: t1..tn, (3) virtual zones: v1..vn (4) computer devices: d1..dn.

7. Discussion

In this section we will briefly discuss the extent to which design models created with the formalism map onto users' mental model of the system. We will also reflect on the approach for the current study.

7.1 Do Users Experience It This Way?

Johnson and Henderson [31] argue that the users' mental model is not accessible to designers in any objective sense, and further point out that different users are likely to have different mental models of a particular interactive system. Our experience from prior usability testing of location and token-based interaction is that implementation specific aspects of a design (e.g. sensor accuracy, visibility of interaction elements, product design, etc.) have a great impact on how end-users perceive such systems [3]. As such, any design model will only represent an ideal and simplified view of an interactive system. However, because interaction with context-aware systems tends to be physical in nature, we consider it likely that aspects such as presence, proximity, and touch are central to how users will understand and describe such systems.

7.2 Reflections on Approach and Results

As with any evaluation, the background of the participants will influence the response. We are aware that a usability expert group is likely to be familiar with concepts that are central to the current formalism (e.g. tokens, zones that can detect user presence, foreground, background, etc.). It is therefore to be expected that that a focus group with a different background may respond differently.

We are also aware that learning how to use any modeling language efficiently requires practice. Thus, issues such as deciding on the appropriate granularity in each frame, might be considered less of a problem given time and training.

8. Conclusions and Future Work

Given the limited scope of the evaluation we consider the current work to represent only the first iteration of a more extensive evaluation process. Nevertheless, it has provided valuable feedback. The key findings can be summarized:

- The formalism appeared to be reasonably intuitive and the expert group quickly managed to combine the notational building blocks into meaningful interaction models. However, deciding on the appropriate granularity of actions to be represented in each frame might be challenging.
- There might be useful to have sublevels or supplementary representations for implementation specific aspects of the designs. Designers also need a formal way to denote the different interaction elements.
- It is primarily a formalism for designers. In order to be comprehensible for user and non-professionals the annotations for interaction elements (users, computer devices, tokens and virtual zones) must be concretized for each particular design.
- The formalism's implicit user-perspective promotes discussion and reflection on design solutions.

The fact that the expert group found the modeling formalism useful suggests that the perspective it provides can be a valuable asset in the design process of interactive systems that support location and token-based interaction.

We view the results from the current work as an incentive for further refinement, development and evaluation of the modeling formalism.

Acknowledgements

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A Comparison of Location and Token-Based Interaction Techniques for Point-of-Care Access to Medical Information

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“You Have a Message Here”: Enhancing Interpersonal Communication in a Hospital Ward with Location-Based Virtual Notes

(METHODS-06)

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