# Indexicality: Understanding Mobile Human-Computer Interaction in Context

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A lot of research has been done within the area of mobile computing and context-awareness over the last 15 years, and the idea of systems adapting to their context has produced promising results for overcoming some of the challenges of user interaction with mobile devices within various specialized domains. However, today it is still the case that only a limited body of theoretically grounded knowledge exists that can explain the relationship between users, mobile system user interfaces, and their context. Lack of such knowledge limits our ability to elevate learning from the mobile systems we develop and study from a concrete to an abstract level. Consequently, the research field is impeded in its ability to leap forward and is limited to incremental steps from one design to the next. Addressing the problem of this void, this article contributes to the body of knowledge about mobile interaction design by promoting a theoretical approach for describing and understanding the relationship between user interface representations and user context. Specifically, we promote the concept of indexicality derived from semiotics as an analytical concept that can be used to describe and understand a design. We illustrate the value of the indexicality concept through an analysis of empirical data from evaluations of three prototype systems in use. Based on our analytical and empirical work we promote the view that users interpret information in a mobile computer user interface through creation of meaningful indexical signs based on the ensemble of context and system.

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## 1. INTRODUCTION

Emerging technologies have made it possible for mobile computers to sense or access information about their user's contextual setting, such as, their physical environment, their location, their social setting, and their current activity [Bardram 2009; Hinckley et al. 2005; Jones et al. 2004; Dey 2001; Dix et al. 2000; Gaver et al. 1999; Crabtree and Rhodes 1998]. Enabled by this, research in mobile human-computer interaction has demonstrated that the usability of mobile computer systems can benefit from making them "context-aware" in the sense that contextual information is used to tailor information and functionality to the given situation [Bardram 2009; Barkhuus and Dey 2003; Kaasinen 2003; Cheverst et al. 2000]. The potential benefits of context-awareness are several. By making mobile computer systems aware of their user's contextual setting, designers can present information and functionality relevant only in specific situations [Barkhuus and Dey 2003; Cheverst et al. 2001]. In this way, the user interface can be simplified and the demand for user interaction can be reduced [Crabtree and Rhodes 1998]. Tailoring the interface to its context may facilitate partial automation of repetitive and trivial tasks [Gaver et al. 1999], and making the system react to contextual changes can also be used to increase security of data and users [Rantanen et al. 2002] and to improve safety-critical applications [Bardram and Nørskov 2008]. Cataloguing information by automatically sensed contextual metadata can be used to supplement human memory through intelligent mobile information retrieval systems [Lamming and Newman 1992]. An example of combining these potentials is systems for the contextually complex domain of healthcare [Bardram and Bossen 2005]. In such systems, work, mobility, and collaboration can be supported through "Activity-Based Computing" and awareness about coworkers [Bardram 2009; Bardram et al. 2006], and information complexity in mobile patient record systems can be reduced by tailoring the interface to the nurse's location, current work activity, patients within proximity, etc. [Skov and Høegh 2006]. Information access could also be supported by making relevant related data and documents from previous similar work activities immediately available [Lamming and Newman 1992].

However, although a lot of research has been done within the area of context-awareness over the last 15 years [Schmidt et al. 2004], since the term was first introduced by Schilit and Theimer [1994], the promise of context-awareness for mobile human-computer interaction has not yet been fully realized in practice. So far, the impact on commercial products has been small, and mostly focused on location. Exceptions include the iPhone's use of context sensors to work out the orientation of the device and adjust the interface accordingly. There are many reasons for the relatively slow transition from the fundamentally sound idea of context-awareness to useful and usable real world mobile systems. We outline a few as follows.

First, the seemingly simple and attractive idea of making technology context-aware hides a large degree of complexity [Brown and Randell 2004]. In practice, even context-aware applications that appear to be very simple, like the mobile phone that only rings where or, more importantly, when appropriate are highly complicated to realize in practice because of the of the deeply complicated nature of context interpretation, for humans as well as for machines.

Second, although a lot of effort has been dedicated to sensing, adapting to, and examining the very complex concept of context [Dourish 2004; Chalmers 2004] and although many definitions exist, mobile computer use context is still not well understood in a way that translates well into mobile interaction design. For example, it is still unclear how the different elements of a user's context influence their interpretation and use of mobile systems. It is also unclear how to utilize knowledge about context, decide what information and functionality to present, what to leave out, and how to make use of information already implicitly present in the user's surroundings [Paay et al. 2009].

Third, only a limited body of knowledge exists that can help explain, theoretically, the relationship between users, mobile system user interfaces, and their context. This lack of knowledge limits our ability to elevate our learning from the mobile systems we develop and study in use, from a concrete level focusing on the specific characteristics of specific systems, to an abstract level where knowledge can be generalized and transferred to other design cases, other technologies, domains, users, purposes, etc. Consequently, the research field is impeded in its ability to move forward in a pace beyond the incremental steps from one design to the next.

It is our belief that addressing and progressing the third issue would also help progress the first two. We believe that expanding the body of theoretical knowledge about the relationship between users, systems, and context holds a key to understanding the concept of context in a way that could inform interaction design better. Jointly, these will reduce the complexity of creating context-aware mobile computer systems and support realizing real world applications in practice.

Contributing to the body of knowledge about mobile interaction design, this article promotes and discusses a theoretical approach for describing and understanding the relationship between user-interface representations and user context. Our purpose has been to create a theoretical foundation for future research and design by developing the concept of indexicality as an analytical lens. This lens applies to mobile user interfaces that carry a major part of their meaning implicitly through the context in which they are used. Achieving this, we have conducted theoretical, technical and empirical research. Our theoretical work has explored the concept of indexicality as a lens for describing and understanding the interpretation of information on mobile computers in context. Our technical work has explored design and implementation of prototype systems making use of indexical interface representations. Finally, our empirical work has used these mobile prototypes as vehicles for studying user interaction in context.

This article advances from our previous work on the topic [Kjeldskov 2002; Kjeldskov and Paay 2006] by presenting the indexicality approach as a detailed and coherent argument and by presenting further empirically grounded analyses of the interplay between users, mobile systems and their context. We also discuss how the concept of indexicality could be used to inform a design process. We do not, however, aspire to present a complete coverage of the topics of context and context-awareness. Nor are we going to provide a step-by-step recipe for how to use indexicality in the design of such systems, but on the basis of the analytical approach presented, we hope that others will be inspired to make such a contribution.

In Section 2 we discuss the concept of context and present a number of definitions and views from related literature. In Section 3 we turn our attention towards the concept of indexicality and how this can be used to explain the relationship between information representations and context. Section 4 presents three mobile prototype systems used for gathering empirical data about use in context, and Section 5 presents evaluations of those prototypes. In Section 6 we present and discuss findings across the evaluations using the concept of indexicality as a theoretical lens for analyzing and understanding the relationships between users, mobile system user interface, and their context. Section 7 discusses how indexicality could be used to inform design. Finally, we summarize, conclude and point towards future research and plans for extending this work.

## 2. CONTEXT

Understanding context is an important part of informing design [Alexander 1964]. There are many different definitions of context, and the debate on what constitutes context for mobile computing is ongoing. Early works on context-aware computing referred to context as primarily the location of people and objects [Schilit and Theimer 1994]. In more recent works, context has been extended to include a broader collection of factors, such as physical and social aspects of an environment [McCullough 2004; Dourish 2004; Bradley and Dunlop 2002; Agre 2001; Dey 2001; Abowd and Mynatt 2000; Schmidt et al. 1999; Crabtree and Rhodes 1998], as well as the activities of users [Bardram 2009].

Dey [2001] characterizes context in the following way: “Context is any information that can be used to characterize the situation of an entity. An entity is a person, place or object that is considered relevant to the interaction between a user and an application, including the user and the application themselves.” Although this definition is quite complete, it is not very specific about what type of information could in fact be used to characterize such a situation. In contrast to this, Schmidt et al. [1999] present a model of context with two distinct categories: human factors and physical environment. Human factors consist of the three categories: information about the user (profile, emotional state, etc.), the user’s social environment (presence of other people, group dynamics, etc.), and the user’s tasks (current activity, goals etc.). Physical environment consist of the three categories: location (absolute and relative position, etc.), infrastructure (computational resources, etc.), and physical conditions (noise, light, etc.). This model provides a good catalogue of specific contextual factors to complement broader definitions like the one proposed by Dey [2001].

Other works are not as comprehensive in their coverage of different contextual factors but go into detail about one or a few. In the works of Agre [2001] and McCullough [2004], particular importance is given to physical context consisting of architectural structures and elements of the built environment, for example, landmarks and pathways. In the works of Dourish [2001, 2004] particular importance is given to social context including interaction with and the behavior of people in an environment. Dourish [2004] also states that context cannot be defined as a stable description of a setting, but instead arises from and is sustained by the activities of people. Hence, it is continually being renegotiated and redefined in the course of action. These works provide us with additional contextual factors of particular relevance to mobile computing in context, and Dourish teaches us that what defines context is in itself contextually dependant.

The purpose of our work has not been to define context or challenge the existing definitions proposed in the literature. Instead, we subscribe to the definition by Dey [2001] and to the fact that several dimensions of context exist and that the relevance of each of these for a particular system or use situation is itself dependent on context. From this starting point, we are interested in explaining and describing relationships between particular dimensions of context and information representations on mobile devices. Our work does not address all dimensions of context mentioned here or in the literature. We have focussed on spatial context (absolute and relative location), physical context, and social context. The reason for choosing these aspects of context is pragmatic. These are aspects of context that are often used in context-aware systems and often discussed in the literature. Hence, we found this to be a suitable starting point. Other aspects of context are, of course, relevant as well. As an example, our three prototype systems also index to activity and temporal aspects of context, albeit not as strongly.

## 3. INDEXICALITY

An interesting theoretical concept for describing and understanding the user interface on a context-aware mobile computer system is that of indexicality. Indexicality is a concept drawn from semiotics describing the relation between representations and the context in which an interpreter perceives them. Taking an indexical/semiotic approach to the analysis of user interface design can contribute to a theoretical understanding of people's interpretation of information representations on context-aware mobile devices. Semiotics is "the study of the social production of meaning through signs" [Scollon and Scollon, 2003, p. 215]. A sign is any material object that refers to something other than itself and, in semiotic theory, includes language, discourse, books, conventional signage (e.g., street signs), the built environment (e.g., roadways and paths indicating places to transit), and people (e.g., through physical presence, movements and gestures) [Scollon and Scollon 2003].

Peirce [1931] developed a triadic model of the sign, commonly known as the semiotic triangle, which considers the representamen (the form a sign takes), the interpretant (the sense made of that sign), and an object to which the sign refers [Chandler 2002]. Simply speaking, signs are viewed as representations of something else (their object) and, faced with a human interpreter, these representations cause a reaction or interpretation (Figure 1).

Peirce [1931] also developed three main categories of signs: symbolic (conventional), iconic (similarity) and indexical (material or causal). Symbols and

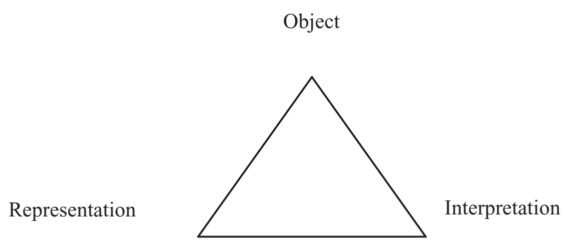


Fig. 1. The semiotic relation between object, representation, and interpretation.

icons are ways of representing information independent of context. A symbol is a sign that is a completely arbitrary representation of something in the world; the sign does not resemble what it is signifying. Examples include alphabetic letters, numbers, Morse code, or national flags. An icon is a picture of something in the world which is perceived as resembling what it signifies. An obvious example is the use of icons in graphical user interfaces, but other examples include portraits, cartoons, or even sound effects [Chandler 2002; Scollon and Scollon 2003].

Indexes, on the other hand, are ways of representing information with a strong relation to their context (for example, spatial and/or temporal) exploiting information present in the interpreter's surroundings. An index is a sign that means something because of where and when it is located in the world. It is not arbitrary and is directly connected, either explicitly or implicitly, to the thing it signifies. Indexical representations are, for example, used on signposts and information boards. Other examples include indexical words, such as, here, there, etc. [Chandler 2002; Scollon and Scollon 2003].

There are many contrasting views in semiotic theory and, taking a purist view of indexicality, Peirce [1931, vol. 2, p. 306] states that, "it would be difficult if not impossible to instance an absolutely pure index or to find a sign absolutely devoid of the indexical quality." A true indexical reference does not require the object of reference to be explicitly indicated, so that in order for it to be successfully interpreted, the interpreter needs to understand the detailed context in which it is given [Chandler 2002]. For the purpose of the work presented in this article, we take a more pragmatic view where indexicality is based on association by contiguity [Martinovski 1995]. An indexical reference is one that relies on a direct connection to an object in the world, through an implicit or explicit representation, that "points to" that object and where the interpretation is reliant on the context of that communication for understanding. Hence, we define indexicality as a property of an information representation that has context-specific meaning. This means that it is dependent on a referent with which it has a relation for its meaning. For example, if a digital display in a train carriage in Denmark reads "Aalborg" when approaching Aalborg train station, it is indexical because of the train's (and, therefore, the sign's) proximity-based relationship to that station. The full meaning of the digital display is "Aalborg is the next station," but some of this information can be left out as it is given implicitly in the context to which the sign is indexing.

**Århus - Langå - Aalborg - Hjørring - Frederikshavn** **Hverdage undtagen lørdage**

| | IC 137 | 5239 | IR 1637 | IC 141 | 5241 | 3139 | 3141 | IC 145 | 3151 | IC 149 | 5249 | 3153 | IC 153 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Århus H | 14.14 | 14.44 | 1 14.44 | 15.14 | | | 15.44 | 16.14 | 16.44 | 17.14 | | 17.52 | 18.14 |
| Hinnerup | \| | 14.59 | 14.59 | \| | | | 16.00 | \| | 16.59 | \| | | 18.05 | \| |
| Hadsten | 14.32 | 15.06 | 15.06 | 15.32 | | | 16.08 | 16.32 | 17.06 | 17.32 | | 18.11 | 18.32 |
| Langå | 14.41 | 15.16 | 15.16 | 15.41 | | 2 15.57 | 16.18 | 16.41 | 17.16 | 17.41 | | 18.20 | 18.41 |
| Randers | 14.50 | 15.26 | 15.26 | 15.50 | | 16.08 | 16.28 | 16.50 | 17.25 | 17.50 | | 18.28 | 18.50 |
| Hobro | 15.07 | 15.46 | 15.46 | 16.07 | | 16.27 | 16.47 | 17.07 | 17.46 | 18.07 | | 18.44 | 19.07 |
| Arden | 15.16 | 15.57 | 15.57 | 16.16 | | 16.37 | 16.58 | 17.16 | 17.57 | 18.16 | | 18.53 | 19.16 |
| Skørping | 15.22 | 16.03 | 16.03 | 16.22 | | 16.43 | 17.04 | 17.22 | 18.04 | 18.22 | | 18.59 | 19.22 |
| Aalborg ○ | 15.39 | 16.20 | 16.20 | 16.39 | | 2 17.00 | 17.22 | 17.39 | 18.20 | 18.39 | | 19.16 | 19.39 |
| Aalborg | 15.46 | 16.26 | 16.26 | | 16.46 | | | 17.46 | | | 18.46 | | 19.46 |
| Brønderslev | 16.06 | 16.45 | 16.45 | | 17.06 | | | 18.06 | | | 19.06 | | 20.06 |
| Vrå | 16.14 | 16.56 | 16.56 | | 17.14 | | | 18.14 | | | 19.14 | | 20.14 |
| Hjørring ○ | 16.22 | 17.04 | 1 17.04 | | 17.22 | | | 18.22 | | | 19.22 | | 20.22 |
| Hjørring | 16.23 | | | | 17.23 | | | 18.23 | | | 19.23 | | 20.23 |
| Sindal | 16.36 | | | | 17.36 | | | 18.36 | | | 19.36 | | 20.36 |
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| Kvissel | \| | | | | 17.47 | | | \| | | | 19.47 | | \| |
| Frederikshavn ○ | 16.52 | | | | 17.55 | | | 18.52 | | | 19.55 | | 20.52 |

1 kun 18/6-3/8
2 fredage samt 27/3, 28/4 og 8/5 ikke 10/5

14

Fig. 2. Page from paper based timetable book: symbolic representations with no indexicality.

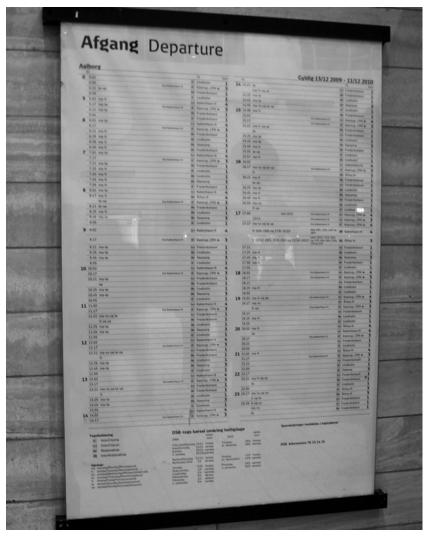


Fig. 3. Timetable poster at a train station: symbolic representation with spatial indexicality.

### 3.1 Reducing Information Representations by Increasing Indexicality

Elaborating on this line of thinking, it is clear that symbolic and iconic representations can be converted into temporal and spatial indexical representations by locating them in time and space. As shown in Kjeldskov [2002], increasing the level indexicality in an information representation by locating it in time and space results in a reduction of symbolic and iconic representations required to communicate a particular piece of information. This inverse relationship is exemplified as follows and illustrated in Figures 2, 3, and 4, which show three different types of information representations related to train departures: a timetable book, a timetable poster in a foyer, and an electronic timetable display on the platform of a train station.

The page from a timetable book shown in Figure 2 exemplifies symbolic (and potentially also iconic) information representation with no indexicality. It contains information about train departures at all times and at all places (within the coverage and valid lifetime of the book). Hence, this representation is valid and useful independent of the user's location in space and time.


Fig. 4. Electronic timetable on platform: spatial and temporal indexicality.

Consequently, the amount of information contained in a book like this is quite extensive.

Figure 3 shows a paper-based timetable poster commonly put up in a central location of a train station. This representation contains a selection of information from the timetable book, namely, information about departures at all times from here (the train station where the poster is on display). Hence, this representation of information is only valid at a particular location, and would be wrong if put on display at a different train station. In relation to the timetable book depicted in Figure 2, the timetable poster in Figure 3 is spatially indexical. As a result, the amount of information is greatly reduced.

The electronic timetable display in Figure 4 exemplifies a further increase of indexicality leading to a further reduction of information. This display contains information about all train departures from here within a short time and is only valid (and relevant) at a specific location and at a specific time. It is a symbolic information representation with spatial and temporal indexicality.

As can be seen from this example, increasing the indexicality, from the paper-based book to the situated electronic display, results in a huge reduction of information to be displayed and of the amount of user interaction required. Instead of having to look up departures from a specific location at a specific time (Figure 2), the user is presented with a reduced selection of information tailored to his or her location (Figure 3) or to location and current time (Figure 4).

From the previous examples, it is also clear that an information representation that has the property of indexicality can only be understood correctly in a particular context. If removed from its context, information will, at best, lose its indexical properties and make little or no sense. At worst, the information representation may take on false meaning. If the digital sign in the train saying "Aalborg" were displayed when leaving Aalborg Station, it would just be confusing or redundant. However, if displayed on a train leaving from a different station and not going to Aalborg it would communicate false information about its destination.

## 3.2 Indexical Interface Design

Andersen [2002] extended the concept of indexical representations into the digital domain by stating that, "pervasive and mobile computing tend towards producing indexical signs, and since the sign can be adapted to its physical context, parts of its meaning can be located in the surrounding place." He also emphasized that this connection between space, time and information is especially important in situations where signs move with the user, such as in the case of mobile computers. Hence, if indexical-type representations can mediate context and exploit knowledge-in-the-world to increase the communicative power of situated information representations, then the concept of indexicality should also be of value for interface design of context-aware mobile computers: to explain, for existing systems, the relationship between information on the screen and its context; and to guide, for new systems, designs that actively explore this indexical relationship.

The potential of applying indexicality as an analytical lens when looking at existing mobile systems in use is that it provides a theoretical foundation on which the relationship between system and context can be analyzed and understood. Looking at the ensemble of context and mobile computer system as a joint indexical sign can help explain why some design solutions work well while others don't. The potential of using the concept of indexicality to inform design is to explore this theoretical understanding by explicitly drawing on the fact that if information and functionality on a mobile computer can be indexed to the user's situation, then information already provided by the context becomes implicit and does not need to be displayed explicitly. In this article, we focus on the potential of using indexicality as an analytical lens.

It is clear that indexicality and context-awareness are closely related. The difference between indexicality and context-awareness is that indexicality is a theoretical concept, while context-awareness is a technical property of a system. Context-aware systems adapt information content to the user's context. Indexicality describes how this contextually adapted information is interpreted. Hence, in short, indexicality can be used to describe, from a theoretical point of view, how and why context-aware systems make sense.

When interacting with a mobile context-aware system the world outside the computer system becomes a part of the interface [Crabtree and Rhodes 1998] and the system's output is interpreted in light of a rich backdrop of implicit information in the context. As in the previous examples, increasing the level of indexicality means that the amount of information explicitly presented to the user can be reduced. This is of great value when designing for the limited screen real estate of a mobile device. As an illustration, a context-aware mobile information service for patrons entering a cinema complex could reduce information in the interface by means of indexical references to time, location and social context. It could, for example, provide only information about upcoming movies playing within a limited frame of time (temporal indexicality) in that specific cinema (spatial indexicality) of interest to a group of users (social context) [Kjeldskov 2002].

## 4. THREE PROTOTYPE SYSTEMS

The preceding examples illustrate that the concept of indexicality can be used as a lens for analyzing and describing information systems in context. However, as the value of an indexical user interface relies strongly on the user's interpretation of and knowledge about their own context, for instance, where and when they are situated, it is important to complement this type of descriptive theoretical analysis with analysis based on empirical data about actual use of such systems. From a theoretically informed analysis grounded in empirical data, it is possible to gain a deeper understanding of how indexicality between user-interfaces and user-contexts functions, in practice, and what potentials and limitations this way of thinking has for interface design.

Following on from our theoretical work, we have developed a series of functional context-aware mobile prototype systems that have served as vehicles for studies of use in real world contexts. Three of these systems are particularly relevant for the argument presented in this article and are described briefly in the following sections. The three systems are similar in that they all run on handheld mobile computers and all represent some level of context-awareness. However, they are very different in terms of their target use domain and purpose. The first prototype, TramMate II, is a mobile route-planning service. The second one, MobileWARD, is a mobile electronic patient record terminal. The third one, Just-for-Us, is a mobile urban guide system.

### 4.1 TramMate II

In 2003, we explored ways of supporting use of the tram-based public transport system in Melbourne, Australia, by means of mobile information systems. This was done through field studies on the use of transportation by business employees attending appointments at different physical locations in the city during a typical workday [Kjeldskov et al. 2003]. As a part of the project, a functional mobile guide prototype was developed by researchers at the University of Melbourne's Department of Geomatics [Smith et al. 2004]. The prototype, here referred to as TramMate II, provided route-planning facilities for the Melbourne tram system based on the user's current location (Figure 5). This was done through a combination of textual instructions and annotated maps.

The TramMate II prototype had three basic functions supporting the use of public transport. The first function was a "Timetable Lookup." This provided timetable information based on stop and route numbers entered by the user (origin and destination) and was aimed at regular tram users who are very familiar with their route. The second function, "Plan Trip," provided information about the whole route, containing route descriptions and maps of the individual segments of the journey. This was based on user entry of origin and destination, suburbs and street corners, and also allowed entry of desired arrival or departure time. The third function, "Determine Route," provided a simplified "Plan Trip" function where the user's origin was resolved via GPS and the system automatically computed an optimal travel plan to a manually entered destination.

The TramMate II prototype was implemented for a Compaq iPAQ handheld computer equipped with a WAP browser. The device was connected to the Internet via GPRS.

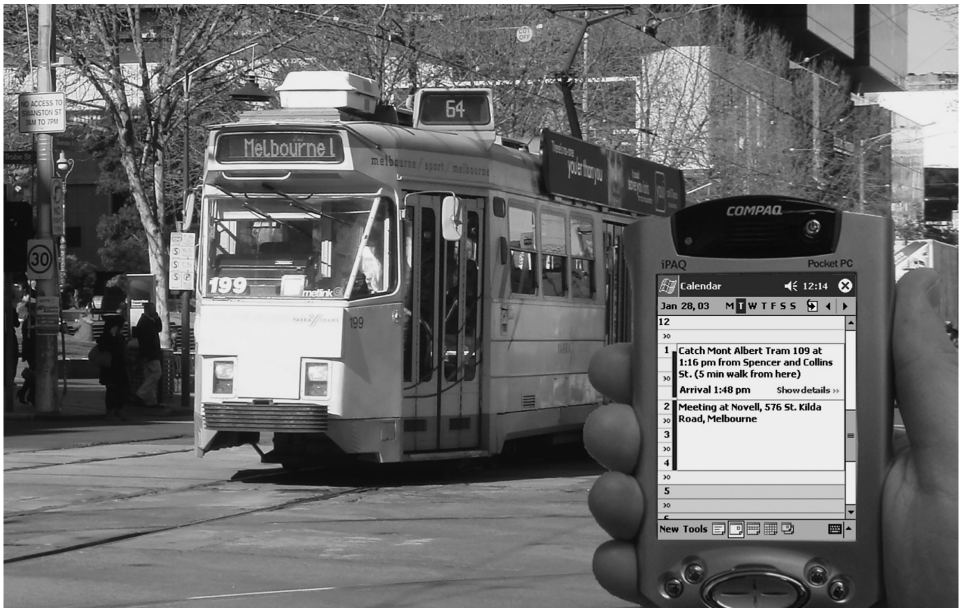


Fig. 5. TramMate II prototype system: route-planning information for the public transport system in Melbourne, Australia, indexed to location, time and physical objects.

### 4.2 MobileWARD

As a part of a larger research activity studying the use of information systems in the healthcare domain, a prototype mobile context-aware electronic patient record (EPR) terminal, refereed to as MobileWARD, was developed at Aalborg University, Denmark [Skov and Høegh 2006]. MobileWARD supports the work activities of nurses during their morning round by keeping track of contextual factors, such as the nurse's location, patients and staff in proximity, upcoming tasks etc. and automatically presents relevant data from the electronic patient record database to the nurse on the basis of this (Figure 6).

In our previous studies of stationary EPR system use at a large regional hospital, we had found that the usefulness of such systems suffered from issues related to mobility, complexity, and lack of relation to work activities [Kjeldskov and Skov 2007]. First, most nurses were concerned about the EPR system not being mobile while many of their work tasks required them to move between different locations. Due to the complexity of information in the EPR system, nurses also had difficulties finding the information necessary for doing their work. Finally, they experienced problems with the use of the EPR system because the data and structure of information in the system did not relate clearly to work activities, locations, and people (nurses, doctors, and patients).

MobileWARD responds to these observations by providing patient data filtered by and indexed to context. When the nurse is in the corridor, the system lists all patients admitted to the ward, highlighting the ones assigned to her.


Fig. 6. MobileWARD prototype system: indexing patient information at a large regional hospital in Denmark to patients in proximity, location and upcoming work activities.

For each patient, MobileWARD provides information about previous tasks, upcoming tasks and upcoming operations. If the nurse wants to view data about a specific patient, she can click on one of the patients on the list. When the nurse enters a ward, the system automatically reduces the list of patients to the ones in that room, hence indexing to that location. By clicking on a patient's name, a detailed view appears with information about previous and upcoming tasks (Figure 6). In order to enter new data into the system, the nurse has to scan a barcode on the patient's wristband. The subsequent information screen indexes to that patient.

The MobileWARD prototype was implemented for a Compaq iPAQ handheld computer connected to an IEEE 802.11b wireless network.

### 4.3 Just-for-Us

The third prototype system is a context-aware urban social guide, referred to as Just-for-Us, developed as part of a collaborative project between The University of Melbourne, Australia, and Aalborg University, Denmark. Just-for-Us facilitates social interactions in the city of Melbourne by providing the user with a simplified digital layer of information about people, places and activities within proximity, adapted to users' physical and social context and their history of social interactions in the city [Paay et al. 2009]. Based on field studies of groups of friends socializing "out on the town," we identified key properties of the physical and social context which people used as reference points in their situated social interactions: the way they communicated and the way they made sense of the world around them. Informed by this, we designed and implemented a functional prototype which pushed the use of


Fig. 7. Just-for-Us: indexing to the user's physical surroundings and history of visits.

indexical references to further extremes than in the previous two designs, in order to gain deeper insight into the use of mobile user interfaces with this particular characteristic.

In the Just-for-Us prototype, indexical links were created between the information in the system and the world surrounding the user through augmented panoramic photographs pushed to the user on the basis of their location. In this way, information in the system is indexed to the user's physical context mediated by an interactive photographic representation. Interacting with this "augmented reality" type of representation, the user can align information in the system with the physical world using information cues in the environment, such as the shape and colour of buildings and major structures. Secondly, information content, such as recommendations of places to go for a certain activity, was reduced by tailoring it to the users current social group (who they are with at that time) and this group's shared history of socializing out on the town. Thirdly, indexical references were used to generate way-finding descriptions referring to the user's familiar paths and places (rather than coordinates, directions and distances) and to visually prominent objects and structures in the user's surroundings (Figure 7).

Just-for-Us was implemented as a web service accessible through a mobile browser. For the prototype we used an HP iPAQ h5550 connected to the Internet through GPRS.

## 5. THREE EVALUATIONS

Because context plays a central role in the interpretation of interaction with a context-aware mobile device from the perspective of indexicality, all three prototypes described previously have been studied during use in the field and

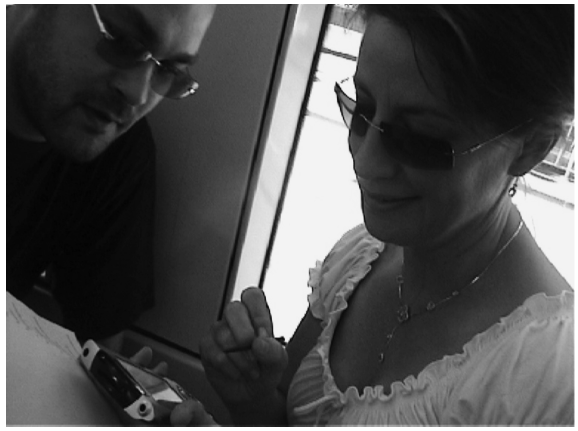

Fig. 8. Field evaluation of TramMate II on board a tram in Melbourne, Australia.

not only in laboratory settings. In the following, we describe the evaluations of the three prototypes involving a total of 62 users.

### 5.1 Evaluating on Public Transport: TramMate II

The TramMate II prototype system was evaluated in Melbourne, Australia, in 2003. This evaluation involved 10 people using the system for 40-90 minutes. All users were familiar with mobile devices and frequent users of the public transport system. Half of the evaluations were carried out in a usability laboratory with the user seated at a desk. The other half was carried out in the field while the user was commuting around the inner city on trams (Figure 8). The evaluations were structured by a series of tasks identical in the lab and in the field. During the evaluations, the users were asked to think aloud and respond to questions from an interviewer. The evaluations were recorded on digital video. In the lab, this included close-up views of the mobile device screen as well as overviews of the user and the interviewer. In the field, the cameraman shifted focus between close-up of the mobile device screen, the user and the interviewer, and overviews of the overall use situation. The TramMate II evaluation is described in detail in Kjeldskov et al. [2005].

### 5.2 Evaluating at the Hospital: MobileWARD

The MobileWARD prototype system was evaluated in Northern Jutland, Denmark, in 2004. This evaluation involved 12 people using the system for 15–40 minutes. All users were trained nurses and familiar with the use of electronic patient records. Half of the evaluations were carried out in a usability laboratory at Aalborg University consisting of several rooms and a hallway furnished to resemble a section of a hospital ward with actors impersonating hospitalized patients (Figure 9). The other half was carried out in situ at a large regional hospital in Fredrikshavn, involving real work tasks and real patients. The evaluations in the laboratory were structured by

Fig. 9. Laboratory evaluation of MobileWARD in a usability lab emulating a hospital ward.

a series of tasks derived from an earlier field study of work activities at the hospital. In the field, we did not enforce researcher control on the evaluations but let real world work tasks prompt use of the system. During the laboratory evaluations, the users were asked to think aloud. For ethical reasons, this was not possible at all times at the hospital. Hence, interview questions were asked during times where the nurses were in the hallway and after the evaluation. In the laboratory, ceiling-mounted motorized cameras captured overviews of the nurses and "patients." Close-up views of the mobile device and user interaction were captured by a small wireless camera attached to the device. In the field, obvious ethical concerns restricted us from filming the nurses' interactions with patients. Therefore only the close-up view of the device was captured while nurses were working in the wards. The MobileWARD evaluation is described in detail in Skov and Høegh [2006].

### 5.3 Evaluating in the City: Just-for-Us

The Just-for-Us prototype system was evaluated in Melbourne, Australia, in 2005. This evaluation involved 40 people (grouped in pairs of two) interacting with the system for 45–70 minutes. Again, half of the evaluation was carried out in a usability laboratory and half of them in the field (Figure 10). All pairs of users were familiar with Federation Square and frequently socialized there together. Being primarily interested in people's use of the system and their response to its indexical information content, neither laboratory nor field evaluations were structured by tasks in the traditional usability evaluation sense. Instead, the evaluations were structured by a set of overall prompts for use of different parts of the system and a list of corresponding interview questions.

Data was collected through note taking and by means of mobile audio/video equipment carried by a cameraman. A wireless camera was attached to the mobile device capturing a close-up image of the screen. This was mixed on the fly with a third-person view of the users allowing high-quality data collection

Fig. 10. Field evaluation of Just-for-Us at Federation Square, Melbourne, Australia.

Fig. 11. Wireless camera on PDA and video recording of participants, interviewer, surroundings and screen.

as well as unobstructed user interaction (Figure 11). Users and interviewer were wearing wireless directional microphones.

## 6. DISCUSSION OF FINDINGS FROM EVALUATIONS

In the following, we present and discuss some of our qualitative findings about the use of mobile computer systems with indexical interface and interaction design from the evaluations of the three prototype systems described above.

Most importantly, we found that, even with a minimum of clues, people are extremely capable of making sense from small pieces of information and information implicitly present in their surroundings. They typically have no problem aligning information in the system with corresponding elements in the physical world surrounding them, including attributing names on the screen to physical places and correlating representations of activities with real work tasks and real people. The indexical references that we found to be most easily understood were those that related very directly to the users' perceived setting, such as their location and the current time. Other well-functioning references were those that align with visually matchable elements in the user's surroundings, such as physical structures and objects nearby.

It was also evident that people used redundant indexical interface references to corroborate their interpretation of the information provided by the systems. They used a redundancy of indexes (i.e., labels, images, signs, structures and activities of others) to make sense of the information presented to them on their mobile computer display and as alternating strategies for matching information in the system to the world around them.

However, we also found that the use of indexical references in digital interaction is different and represents a greater risk when getting it wrong compared to the use of indexical references in face-to-face communication. It is much more difficult for a computer system than for a person to gauge a person's reaction to an instruction or a piece of information and adapt to that reaction through additional information or meta-communication, if we realize that more information is needed for clarification or that we have been misunderstood. In reducing the amount of information presented in the user interface of a mobile computer user interface, it becomes increasingly important that the information that remains still provides the right clues for the user to interpret it correctly on the basis of their context.

In the following, we present and discuss findings related specifically to indexing to physical context: physical context (architectural structures and elements of the built environment), spatial context (location), and social context (presence and behavior of other people).

### 6.1 Indexing to Physical Context

The three prototype systems all indexed to the user's physical context. They all had information content directly related to specific physical entities and structures in the users' physical surroundings, such as trams, tram stops, wards, venues, and landmarks. The indexical relationship between the information in the system (the sign) and the entity they were referring to (their object) was supported through textual-type references, such as descriptors like "the next tram" or "the black building," and through iconic-type references like pictures of noticeable structures, logos, drawings, and maps.

From our evaluations, we found that indexing mobile computer systems to physical context is not difficult for people to interpret and understand and that people readily use a variety of indexes to physical context to create meaningful indexical signs out of the ensemble of user interface and use context.

When looking at the usefulness of particular types of indexical references to physical context, we observed that people were particularly good at using visually prominent outlines of their immediate surroundings (for example, the layout of a room, the shape of nearby buildings and structures, the shape of distant structures, or parts of the skyline) to align the system with their surroundings. From there they would create a meaningful indexical sign out of the information presented on the screen in their particular physical context. People also used the presence of distinct physical objects to create indexical signs. This included distinct physical objects in their immediate surrounds (for example, colored walls, media screens, satellite dishes, tram stops, trams, beds) as well as in their distant surrounds (for example, a river, a church, a train station, and a distant tram.)

Related to this, we also found that people frequently used labels and headings in the system to match up with labels and signposts in their physical surroundings in order to make meaning out of their mobile computer system. They expressed a clear expectation to be able to find such matches, and conversely, they also expected clear labels and signs in the physical world to appear in the system. The matching up of labels and signs happened not only textually but also iconicly in terms of the visual style of labels and signposts across system and context, notably, that of logos.

Other types of useful indexical references to physical context were not based on support through visual similarity. Using a distinct physical quality of an object or a place as descriptor, for example, "the black building," "the glass wall," or "the old tram," was also found to be very useful reference type for the creation of meaningful indexical signs. It was also observed that using these types of indexical references allowed information content to be indexed to physical context beyond the users immediately visible physical surroundings to, for example, familiar places nearby (such as landmarks, specific high-rise buildings, railway stations, tram stops, wards, offices, etc.) with distinct physical features.

Indexing to physical context through descriptive references to distinct features that the users know through their familiarity with a place was found to be a valuable way of reducing information for expert or repeat users of a system, such as nurses using MobileWARD or frequent travelers in the city using TramMate. Indexing to distinct features in the physical context was also found to be of value as key anchor points in way-finding instructions for people who are new to a place, such as tourists using the Just-for-Us system. In terms of way finding, we found that such indexical references work well because they replicate the way we often give directions to others: pointing out distinct feature in the physical surroundings along a path to the given destination, allowing people to operate with greater flexibility in between those anchor points.

6.1.1 *Redundancy and the Sufficiency of Approximation.* On a general level, we found that, when indexing content in a mobile computer system to physical context, there are two things to take particular notice of: redundancy and the sufficiency of approximation.

When faced with an indexical reference, there is always a risk of misinterpreting that to which is being referred. From our evaluations, we observed that people appear quite used to this risk and make use of a redundancy of references to support and confirm their interpretation (not dissimilar to triangulation in data analysis). As an example of redundant indexical references in our prototype systems, textual labels often complemented images and maps, which allowed people to double-check their interpretation based on one of those by testing it through the other. For example, having interpreted from a layout representation of a ward that the patient in the bed to the right is named "Marie Frandsen," this can be confirmed by comparing this name to the label on the bed or patient and vice versa.

In the use of text-based and icon-based indexical references described previously, we found that there was not a strong need for representations that matched exactly with the user's physical context. People's responses to the use of skylines, outlines of buildings, layout of rooms and areas, and overall shape and appearance of distinct physical objects and landmarks indicates that these approximated representations are sufficient enough for meaningful indexical signs to be formed. This sufficiency of approximation was also observed for textual references to features in physical context where it was found that people apply quite broad interpretations of descriptors like "black," "tall," "old," etc. in order for the indexical reference to make sense. Sufficiency of approximation was also observed in relation to the text and visual appearance of labels, signage and logos.

### 6.2 Indexing to Spatial Context

The three prototype systems all indexed to the user's spatial context. They all presented information related to the users' absolute as well as relative location, such as what tram stop they were at, how far they were from a tram stop, which room they were in at the hospital (ward, hallway, office, etc.) and which venue at Federation Square they were at. The indexical relationship between information in the system and the location it related to was usually not supported by means other than the users' presence at a particular location and a simple label describing the system's interpretation of this location such as "Stop 7," "Ward 254" or "Main Plaza."

From our evaluations, we found that people generally understand when a mobile system adapts to their current location and that this type of adaptation is usually found to be useful. Our observations showed that when indexing information on the screen of a mobile computer system to the user's spatial context, this relationship is easily understood, and the ensemble of system and context is interpreted as a joint indexical sign. We believe that this observation reflects the fact that we are very familiar with spatial indexicality through our life long experience of language and signage that relates specifically to its location, and that we are very experienced with the interpretation of such signs. Hence, as we observed, it is easily accepted that an electronic sign (the mobile computer screen) should be understood in a similar way through interpretation of its implicit references to the location in which it is situated.

As with indexing to physical context, we found that approximation of spatial context was also sufficient when it was possible to identify notable spatial areas (e.g., trams, wards, plazas, and bars). Hence, for the specific prototype systems evaluated, using such places or areas as an approximation of current location, rather than using precise Cartesian coordinates, was found to be entirely adequate for the correct interpretation of information. In fact, approximating spatial context to specific places or areas corresponds well to the way we are used to experiencing our spatial context as human beings situated in the world. Hence, making use of such approximations explores our life long experience of interpreting our own spatial context. In some situations, however, it might not be possible to make such approximations, in which case more precise location information is needed, or indexical references will have to be made open for broader interpretation.

Although people understood the indexical signs produced jointly by the mobile computer system and their spatial context and appreciated this kind of system behaviour, we also observed that the reduction of information resulting from indexing to spatial context sometimes had the unintended effect of overly limiting the amount of information available to the user. In response to the prototype system automatically converting information into spatially indexical signs, we observed that people were sometimes not fully satisfied with this reduced subset of information and expressed a need or desire for information beyond their current spatial context: information about other trams, other wards, other venues, etc. This finding led us to conclude that although spatial indexicality can be a powerful means of reducing information on mobile computer systems through the creation of indexical signs, the fact that this particular sign is also interactive and networked comes with an inherent set of user expectations about information being available any time and anywhere, that is, independent of context.

6.2.1 *Trust and Control.* Taking a step back, we found two things to be particularly aware of when indexing content on a mobile computer system to spatial context: trust and control.

In response to the system knowing the users' location, we observed the unexpected side effect that people perceived the system's information content as true. For the purpose of the evaluations of MobileWARD and Just-for-Us, this was actually not always the case because of ethical and copyright-related issues. Nevertheless, for example, some people actually pursued ordering from the made-up menu of a café presented to them by the system at that place, trusting that the content of the spatially indexical sign was indeed true. The reverse effect was, however, just as strong when the system got the user's location wrong and, therefore, appeared "unpredictable" as discussed by Cheverst et al. [2000]. Such loss of trust was observed when, for example, TramMate II displayed a wrong stop number at a critical point of the journey and when MobileWARD displayed information related to a ward when the user was actually in the corridor. These and similar behaviors were caused by technical bugs but the effect on the user experience brings to attention the importance of spatially indexical systems being robust in their ability to sense and adapt correctly to their spatial context, as also discussed by Schmidt-Belz [2003].

Somewhat related to the issue of trust is the issue of control. While people understood that the systems adapted to location, they were sometimes uncertain about how to then control the system. The observed issues of control related to situations where the users wanted to stop the system from automatically pushing new content due to a change of location. This happened either because the users still needed the information automatically presented to them at their previous location or because they had manually navigated to a piece of information that they wanted to keep ready at hand. In both cases, the systems sometimes took this level of control away from the user. Giving control back to the user could be done through ways of stopping or pausing automatic updates, making newly pushed information appear without completely taking away what was already there, or, at the very least, by giving the user an option for browsing backwards at any point in time (or place).

### 6.3 Indexing to Social Context

MobileWARD and Just-for-Us both contained indexical references to social context. They presented information related to the presence and activity or state of other people in the user's surroundings such as patients, friends, and groups in vicinity. The indexical relationship between information in the system and the user's social context was supported only by simple textual labels, like "Marie Frandsen" in MobileWARD or through "social activity meters" depicting the amount of people at different places in Just-for-Us, revealing the system's simplified interpretation of the user's social context.

From our evaluations we found that indexing mobile computer systems to social context can be more difficult for people to understand than when indexing to physical or spatial context. People often had difficulties interpreting the presented information as a meaningful indexical sign when it was indexed to their social context. In order to interpret this type of indexical reference, they often needed a more detailed explanation about what the system was doing and what the system knew about its context. Once having learned how a system adapted to the user's social context, this interpretation improved.

Relating back to the use of descriptors in indexing to physical context, we found that for social context using descriptors based on social activities, such as "the sitting steps," was not found to be useful. This is because they relied on ephemeral conditions surrounding those places and objects, and people were concerned they were too unclear and open for wrong interpretations when, for example, nobody was actually sitting on those steps. This was surprising, because most people knew which steps were meant based on their experience of the place and on the physical affordances of those steps.

One of the ways where indexing to social context did work well was in relation to way-finding descriptions provided to a social group rather than to an individual. Here we found that the use of references to shared familiar places and shared past social visits were useful. Instructions were related to the groups' joint memory and knowledge of an area and also anchored naturally in to their unique shared history and patterns of social interactions. Similarly to the way rhythms of work activities over time were observed to facilitate information seeking by interpretation, Reddy and Dourish [2002], rhythms of social activities over time also seemed to facilitate information thus linking social context closely to activity and temporal context. We believe that this observation reflects the fact that this is, again, how we are used to making use of social context to reduce complexity in face-to-face interaction: describing the location of places with reference to other places that we know that person is familiar with or that we both know through prior shared experiences. For example, planning to meet at "the place we met for dinner last time."

Rhythms of activities are integrated parts of our everyday life and manifest themselves in many ways [Zerubavel 1979, 1985]. This pervasiveness of rhythms makes them a compelling focus for the development of information tools [Reddy and Dourish 2002; Begole and Tang 2007; Bellotti et al. 2008] because people have a strong and shared sense of temporal patterns of activities and use these to coordinate, form expectations, etc. From the perspective of context-aware mobile systems, rhythms of social activities over time could in themselves very well constitute an important, derivative, dimension of context.

On a side note to this, once knowing how a system made use of people's history and rhythm of social interactions, many people expressed concerns and uncertainty about how to control this system behavior in relation to issues of privacy.

6.3.1 *Subtle Context and Making the Implicit Explicit.* In looking at people's use of indexes to social context, we found the following two things particularly important to consider: subtle context and making the implicit explicit.

As just described, we found that socially contextual factors, indexed to by the system, were much less obvious to people than their physical and spatial context. Thus, people's interpretation of information on the screen often failed to take those subtle social context factors into consideration. People sometimes simply didn't expect, or understand very well that the system knew about their current social setting and was capable of adapting and indexing its content to this context. Missing the subtle clues of social context was mostly obvious in the evaluation of Just-for-Us, which was designed specifically to facilitate social interactions. This system had access to socially contextual information, like whom you were with at the time, and your friends' and your individual as well as shared history and rhythm of social interactions. It then generated ranked suggestions for where to go based on patterns in the current social group's shared history and rhythm. In the use of this particular and quite advanced functionality, we observed that people completely failed to interpret the indexical reference to their social context. Consequently, the information held no meaning for them or was misinterpreted in different ways (i.e., vendors paying for rankings). We believe that this observation reflects a fundamental difference between social and physical/spatial context. As social context is not only about whom you are with but also very much about your history and rhythm of social interactions with this group of people, social context is not only often implicit but also largely invisible and something that is peripheral to us. This makes social context harder to index to in a computer system, and it makes it harder to interpret a socially indexical sign correctly.

One thing that we found did work very well in terms of indexing to social context in our evaluations of both MobileWARD and Just-for-Us was representing social context information. Specifically, we found that people like to get an overview of their social context, such as the presence and activities of other people in the surrounding environment. This information was presented in different ways in the MobileWARD and Just-for-Us system, but in common for both, they provided not only new and valuable information in themselves, but also objectified social context which could then be indexed to more successfully. In terms of the limitations of subtle factors of social context in the creation of meaningful indexical signs, representing social context in this way increases the potential for making interpretable indexical references to social context by taking something implicit and invisible and making it explicit and visible.

## 7. USING INDEXICALITY IN DESIGN

How can we use indexicality in the design of mobile and context-aware systems? In response to this challenge it is important to note that indexicality is not a design tool or method. It is purely a concept that can be used to describe and understand an aspect of a design. This is not unique to the concept of indexicality, though. Exactly the same can be said for established principles within human-computer interaction, such as mapping, affordances, the Gestalt principles, and so on. These are theoretically grounded principles that can be used to describe features of a design. By understanding such principles, they can be used to inform the design process. Doing the latter is perhaps the hard part, though. How do we transcend from the retrospective activity of analysis through a certain theoretical lens to the proactive activity of designing through it? In line with Alexander's [1964], [Alexander et al. 1977] views on the activity of design, we believe that good design requires a solid understanding of its context and of the principles that previous solutions have shown can be successfully applied. Interaction design for mobile devices involves several such principles. Some are related to optimising limited screen real estate and some are related to the use input devices on mobiles. The principle of indexicality would relate to the interplay between user, system and context.

In Alexander's own work, such principles take the form of design patterns [Alexander et al. 1977], each exemplifying design challenge, theoretical understanding, and possible solutions. This makes them particularly accessible and useful for designers. They are grounded in massive empirical evidence and solid understanding but provide guidance for design that is specific enough to inspire solutions while general enough not to prescribe them. One of the things that make established design principles within human-computer interaction useful in design is that, similar to Alexander's design patterns in architecture, a body of empirically grounded examples have evolved in their support. This makes underlying theories and concepts (e.g., cognition and perception) much more practically accessible and, hence, those theories are in effect being used more to inform design. Such patterns and examples are yet to evolve for indexicality as a principle for mobile interaction design and would support the process of designing systems on the basis of this concept greatly. Developing such design patterns would involve analyzing and describing indexical properties of other successful existing context-aware systems apart from the few ones discussed here.

Apart from understanding the indexical interplay between users, systems, and context and having access to patterns of indexical design solutions in other systems, using indexicality in design requires knowledge about what specific elements in the users context they can be indexed to for the system being developed. This requires the identification of indexable attributes of the context during the projects' analysis phase. Our own work within this area includes structured mappings of physical, spatial and social context using a multidisciplinary socio-physical approach [Paay et al. 2009] and illustrates one possible process to follow. Other processes may involve more stringent techniques for identifying the contextual information that a mobile system might index to.

## 8. SUMMARY AND CONCLUSIONS

This article has promoted the concept of indexicality as a theoretical concept for describing and understanding the relationship between user interface representations and user context for mobile human-computer interaction. We have argued that the lack of a theoretically grounded body of knowledge that explains this relationship is limiting our ability to elevate learning from the mobile systems we develop and study in use from a concrete to an abstract level. Consequently, the research field is impeded in its ability to leap forward beyond the pace of, at best, incremental steps from one design to another. In response to this lack of theoretically grounded knowledge, we have explored the semiotic concept of indexicality as an analytical concept that can be used to explain the user experience of a specific design in context. We have illustrated the analytical power of this concept through the analysis of a mobile interaction design concept and through the analysis of empirical data from three studies of context-aware mobile computer systems in use: TramMate II, MobileWARD, and Just-for-Us.

Our findings show that by applying the lens of indexicality, new and theoretically grounded knowledge can be generated from empirical data about mobile human-computer interaction in context. We have found that even with a minimum of clues, people are extremely capable of making sense from small pieces of information in a user interface if they can be meaningfully indexed to their surroundings. People interpret mobile computer systems in context as joint indexical signs carrying their meaning through the ensemble of implicit context and explicit interface representations. In the design of such interfaces, this indexical interpretation allows the amount of information explicitly presented to the user to be reduced. This is particularly valuable when designing for systems with small graphical user interfaces, such as handheld computers, and for situations where users have limited or divided attention towards the system, such as most mobile use contexts.

The indexical references that we found to be most easily understood were those that related the users' objectively perceivable settings, such as their location and the current time. Other well-functioning indexical references were those that related to visually matchable elements in the user's surrounding, such as prominent physical structures and objects nearby. Indexes to social context were found to be more difficult for users to interpret correctly, and we speculate that this is caused by the intangible and peripheral nature of this type of context compared to location, surroundings, activity and time.

In terms of indexing to physical context, we conclude that this is not difficult for people to interpret and understand, that people use redundancy of indexes to physical context to create meaningful indexical signs, and that they double check their interpretation of one against another. We also conclude that there is a sufficiency of approximation associated with representations that index to physical context through iconic and symbolic references.

In terms of indexing to spatial context, we conclude that this is easily understood and that the ensemble of user interface and user context is interpreted as one joint indexical sign. In relation to this, we have highlighted the potential impact of spatial indexicality on the users' experience of control over what the system is doing and their experience of trust in the content that is provided when a system adapts correctly to its location.

In terms of indexing to social context, we conclude that this is more difficult for people to understand than when indexing to physical or spatial context. Social context is subtle and often invisible and implicit and, in order to understand socially indexical references, people need to be made aware about what the system knows about their social context and what aspects of it are being indexed to. We describe this as making the implicit explicit.

Inspiring further research, the findings from the three studies of use in context discussed previously also revealed a series of challenges for indexical interaction design for mobile computer systems. In relation to the issues of control and trust, people rightfully raise issues about their privacy when faced with a system that indexes to their current and history of spatial and social context. In order to make systems spatially and socially indexical, it is important that the users trust them enough to allow collection and reference to this information. One of the central components in the creation of such trust is the availability of transparent means of user control.

It also appears that different people and different situations require different levels of indexicality and that there is no such thing as universally appropriate indexical references when it comes to complex digital signs, such as interactive mobile computer systems in context. Using redundant indexical references allows some level of flexibility in interpretation but, as we are dealing with interactive signs here, it would be interesting to explore the possibility of developing a mechanism allowing the user to manually adjust the level of indexicality in the interface: reducing or increasing the strength of implicitness and consequently increasing or reducing the amount of explicitness.

## 9. FURTHER WORK

In terms of realizing indexical interface design in practice, there are two particular things that we find need additional work. Firstly, for system developers and interaction designers to be able to index to elements in the users context, a solid understanding of the indexable attributes of a specific environment needs to be gathered during the projects' analysis phase. Our work within this area includes making structured mappings of physical, spatial and social context in a particular place using a interdisciplinary socio-physical approach [Paay et al. 2009]. However, this work is not complete and needs to be extended further. Secondly, designing explicitly with the concept of indexicality in mind is, like any other concept, likely to benefit from additional support in the form of design heuristics, guidelines or patterns outlining challenges and generally well functioning design solutions. However, the creation of such heuristics, guidelines or patterns rely on the cumulative formation of a body of knowledge about design challenges and corresponding indexical design solutions. Here, we have described what we have learned from three specific systems through the theoretical lens of indexicality. More studies of mobile human-computer interaction in context are needed through the same theoretical lens in order to create general guidelines for indexical interaction design.

Further research also needs to extend the range of contextual factors indexed to, for example, the aspects of context related to activity, time and other information. This could also include a systematic decomposition of the different aspects of context and related sources of information that a system might provide an index to.

Finally, the generalizability of the analytical power of the concept of indexicality for describing and explaining the user experience of mobile systems in context should be investigated beyond the three prototype systems discussed here. As a starting point, it would be interesting to look at other successful context-aware systems through the lens of indexicality.

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