# Mental Models of Disappearing Systems: Challenges for a Better Understanding

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**Abstract.** In this paper, we describe our current research concerning users' mental models of what can be called "disappearing computer systems". This notion comprises computer systems, applications, and appliances related to ubiquitous, pervasive, or ambient computing which blend more or less seamlessly into the users' natural environment. Mental models enable users to formulate expectations about which interactions with the system are possible and how the system will react to certain interactions. Disappearing computers lack certain cues regarding the inner workings of the system. We thus hypothesize that the mental models users build of such a system will show defects and inaccuracies that are directly related to the distributed character of interface and interaction. Our current research aims at identifying the nature of these defects, understanding their effects on human computer interaction, and developing means of avoiding them through appropriate design of both user interface and underlying system. For this purpose, we are developing an ambient, context aware computing framework with which we generate and test hypotheses in an action research paradigm. One of its components will be described along with possible future additions. The theoretical foundation of our work lies in such diverse fields as systemic functional theory of language, activity theory, and cognitive science approaches to mental models.

## 1 Introduction

The computer as we know it, namely as a box equipped with monitor, keyboard, and mouse, is appended with systems that are not easily identifiable as computer systems. For the last three decades, these boxes have become an increasingly important part of most peoples' everyday life in work, education, and leisure, and the exploding feature sets of modern Personal Computers have in practice turned them into the "universal machines" that they were theoretically from the very beginning. But for some ten years now, another tendency can be observed. The Personal Computer as a single, distinct, and discrete information processing device is being augmented and partially supplanted. Advances in silicon circuitry and wireless data transmission technologies have made it possible to put more processing power, storage space, and communication interfaces in ever shrinking devices, which in turn leads to the transformation of formerly analog or mechanical, unconnected devices into computer-enhanced, connected systems.

### 1.1 Disappearing Computers

These recent developments that usually go by the name of pervasive or ubiquitous computing have been the object of extensive scientific and public discourse (cf. [15,25,29]). The interconnections between these miniature computers form a sort of meta-computer that is spatially (and temporally) spread across potentially large areas: instead of a single computer serving a single person we now have several computers serving one or several persons.

In addition, instead of utilizing distinct user interfaces, such as screens, keyboards, and mice, they are often embedded into other artifacts, and any interaction with any such artifact becomes interaction with the computer. To capture these changes, the term ambient computing was coined. The term ambient intelligence describes the ability of systems to become more proactive and make assumptions about their surroundings or their users on their own accord [7].

For the purpose of this paper, all computer systems that can be named under either of these terms (ubiquitous, pervasive, or ambient computing) share one important property: partial or complete invisibility. Such systems do not appear as distinct and discrete computers as the PC once did. Instead, they vanish within the artifacts they are embedded in. They usually also do not have the prominent and familiar in- and output devices for user interaction that PCs have. So it is not only the physical box that is disappearing, but also the interaction with the system. Formerly, human-computer interaction took place at one particular place, namely at one's desk, and at a particular point in time, namely when one typed on the keyboard or used the mouse to point and click. With disappearing computers, the artifacts and events shaping the in- and output of the system are not necessarily recognizable as interfaces of and interaction with computer systems.

In summary, these are the reasons why we speak of disappearing computer systems (cf. Norman [20]). The twofold disappearance of computers raises numerous questions with regard to the design principles of their user interfaces and the way the inner working mechanisms of the system are conveyed to the user. Section 2 below will outline our thoughts on this topic.

### 1.2 Mental Models

In virtually all situations in everyday life, people rely on mental models of relevant aspects of the world in order to evaluate the situation, plan their actions, and formulate expectations of the outcome of these actions [19]. Literature reveals that different domains have different definitions of mental models and have established a wide range of theories about how these models are built, chosen to fit a particular situation, and made use of [23]. In their comprehensive review of literature dealing with mental models, Rouse and Morris [23] deliver a functional definition of mental models that is well suited for the needs of designers of complex systems: "Mental models are mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states". It is repeatedly shown that mental models can be extremely complex and are individual to the respective person, since they are usually elaborated over time and linked to other mental models and knowledge about the world (cf. [11,30]).

This leads to three main characteristics of mental models (cf. Dutke [8]) that must be taken into account when using them to assess the usability of disappearing computer systems.

1. Mental models are never complete or exhaustive when compared to the real world. There are always more details to include in the model, and this refinement seems to be limited only by the trade-off between the model's complexity and its useful applicability in actual situations.
2. Mental models are resistant to changes. This is basically due to the fact that changing existing models requires learning effort, and thus there is a trade-off between this effort and the perceived usefulness of the resulting improvement of the mental model.
3. Mental models are unstable, since people tend to forget details of their once-acquired mental models over time.

Norman [19] summarizes that "most people's understanding of the devices they interact with is surprisingly meager, imprecisely specified, and full of inconsistencies, gaps, and idiosyncratic quirks". And, we would like to add, it is the foremost duty not only of user interface designers, but of system engineers as well, to account for these quirks and build their systems to deliver an untroubled user experience. How this can be done is the subject of our current research.

## 2 Understanding and Shaping Mental Models

We have recently begun working on the topic of mental models in users of disappearing computer systems, because this class of systems raises questions that cannot be answered satisfyingly with current theories of mental models. Our approach is twofold. On the one hand, we address the analysis of the mechanisms which affect the building of mental models in such users. On the other hand, we aim at identifying design principles that foster development of useful and adequate mental models.

Research on ambient and context aware systems needs to address different levels of scientific insight. On the one hand, the concepts of "context" and "awareness" need to be explored, as they form a crucial part of our understanding of the situatedness of a user's perception and use of disappearing computer systems. On the other hand, building upon this theoretical foundation, we also need real ambient systems with which we can test our hypotheses, derive new ones, and explore the regularities of various facets of human-computer interaction in this domain.

### 2.1 Challenges for Mental Models of Disappearing Systems

The functionality of disappearing computer systems as described in the Introduction is often achieved by collecting a large variety of data via distributed sensor nodes. Often this data is also (pre-) processed and the results are delivered back to the user in a distributed way. Our research concerns primarily systems that become more proactive and learn, often referred to as ambient intelligence. Ducatel and others [7] give a definition of ambient intelligence: At the core of an ambient intelligent system lies the ability to appreciate the system's environment, be aware of persons in this environment, and respond intelligently to their needs.

We postulate that challenges to the development of suitable mental models for ambient intelligent and disappearing computer systems emerge along two dimensions:

First, the environment and artifacts become the interface, with the difficulty of exhibiting suitable affordances for its use. For traditional computer systems, it is considered good practice to provide good affordances, that is to provide interaction possibilities that are readily perceivable by a user [21]. This becomes difficult when artifacts in the environment are charged with additional functionality. For example, Bob might usually take a bowl of muesli in his lunch breaks. Taking this bowl and going out of the office can now be perceived by an ambient system as a sign that Bob is having a break, thus overloading the bowl with additional functionality. It is not obvious how this function of the bowl can be easily communicated to the user.

Second, as the technical system becomes proactive, it might produce new and surprising results, or change itself as well as the environment, possibly without direct user interaction. For example, if one of Bob's meetings takes longer than expected, an advanced ambient system might re-schedule Bob's later appointments without disturbing the current meeting. This is the classical problem of traditional, non-ambient artificial intelligent systems. A promising way to deal with this challenge is to provide explanations about actions taken and reasoning performed [17].

Ambient intelligent systems face challenges on both dimensions at the same time: the aforementioned muesli bowl is now only one part of the sensor network, and its absence or presence might or might not be taken into account to decide whether Bob is having a break, all depending on other sensor data and system states. This function of the bowl has to be communicated to the user, but there is no easy way to deliver explanations: probably, there are no classical interfaces. Even if there were, using them would mean that the artifact immediately looses its ambient character.

### 2.2 Theory Construction

With regard to the theoretical foundations of our work, we draw from recent work in context awareness [12], explanation awareness [4,13], and theories of ambient user interface design [5].

Our take on disappearing systems as having some form of artificial intelligence forms the backdrop for exploring methods to better understand how mental models of such systems are formed, what influences their shaping, and for formulating methods to use the understanding gained to support the development process of ambient intelligent systems.

To achieve this, we make use of theories from the fields of cognitive science, human-computer interaction, psychology, sociology, and linguistics. The specific theoretical frameworks we draw on are, first and foremost, activity theory [14] and the systemic functional theory of language (SFL) [10], a social semiotic framework.

A major problem with research of this nature, research which attempts to integrate theories from diverse areas of practice, is the perception that there are very different underlying philosophies. This is of particular importance when trying to integrate the strengths of theories for the purposes of solving real world problems. Both activity theory and SFL have been used in the field of ambient intelligence and explanation awareness [4,28,31].

Following Carley and Palmquist [3], who have examined mental models from a symbolic, language perspective, we utilize SFL to understand how users' mental models are formed. We deem SFL particularly useful because it looks at language in a very general sense as a means of interaction. We interact not just with each other, but with our own constructions and with our natural world, and this interaction is inherently multimodal [9]. Another perspective on mental models in relation to language is given by van Dijk's [6] theory of mental and context models. Van Dijk himself is influenced by SFL and episodic memory as proposed by Schank [26].

But our mental models are not only shaped by acts of communication, they are also construed by our acting on and with artifacts. Therefore, in our research, we explore to which extent it is possible to relate a semiotic approach to activity theory. Bødker and Andersen have outlined some properties of a socio-technical approach taking advantage of ideas from both theoretical frameworks [2], and we would like to extend this to cover specific aspects of SFL and cultural-historical activity theory (CHAT, cf. [18]). This will potentially lead to a richer understanding of the different aspects of mental models as both result and prerequisite of communication and of manipulation of artifacts.

### 2.3 Empirical Evaluation

Our primary scenario for the empirical part of our work is that of an ambient, intelligent system aimed at facilitating cooperation and mutual awareness in work teams (cf. Sect. 2.4). We chose this scenario since, due to the system's distribution in time and space, the users' interaction with the system's intelligent functions will partly be implicit. That means that the system might, for example, change users' interruptibility status or spatial location information without being told to do so by explicit user interaction or without direct announcement of such changes to its users. The system should also be able to infer correct information even from incomplete or inconsistent source data. This reasoning capability requires a large amount of data from various sources, aggregated and processed into a knowledge model, and suitable inference mechanisms. Even if we expect the system to draw the correct inferences, it seems obvious that the system would need some kind of explanation component in order to make clear to the user why a specific decision has been made. In particular, what peculiarities in the data set or reasoning mechanism have led to a different decision than in a previous, albeit superficially similar situation [4].

In a system with sufficiently high complexity and numerous data sources to be useful for real-life tasks, simply printing out the chain of firing production rules or best-matched cases on a screen would surely confuse the user more than it would help [16] as well as if, e.g. a neural network or other subsymbolic system was part of the decision process, this display of the reasoning trace would either not be possible at all or very difficult. Thus, it is of great importance for the usability of ambient computer systems that they are able to explain themselves in an unobtrusive, yet comprehensive and sufficiently detailed way. How this can be achieved is subject to our current research.

### 2.4 The MATe Framework

The MATe system is a family of appliances, client- and server-based software that aims at improving situation awareness in work teams. The acronym MATe stands for "Mate for Awareness in Teams". The system is designed to blend seamlessly with the team members' everyday routine, enabling unobtrusive in-situ interaction and facilitation of cooperation and communication. Currently, MATe consists of several components (see Fig. 1), which we will briefly describe, and is being implemented at our institute.

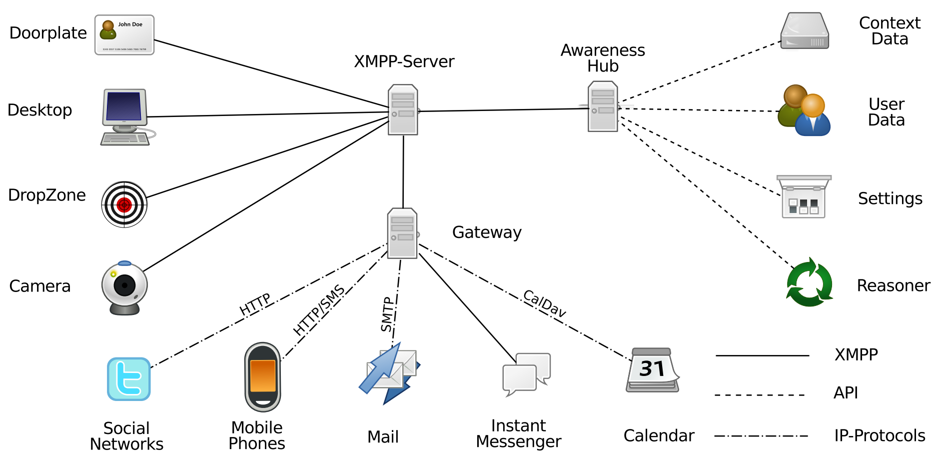


**Fig. 1.** MATe: Architectural Overview

**AwarenessHub.** The AwarenessHub is the central service to which all other components connect. It handles all communication among the components and takes care of the correct routing of messages and the appropriate processing of different pieces of information. Technically, the AwarenessHub is implemented as a client which can connect to any instant messaging server using the Extensible Messaging and Presence Protocol (XMPP[1]). It has all other components of one specific MATe installation in its contact list and can thus exchange XMPP messages conforming to the MATe protocol specification with them.

Since it is not guaranteed that the information available to the AwarenessHub will be consistent at all times, a component for resolving conflicting status indications is needed. It might be that a user forgot his keys in someone else's office, but went out for lunch anyway, while not having corrected a calendar entry concerning a meeting with another colleague. MATe should be able to deduce reliable information about the users' current status and spatial position by applying appropriate reasoning techniques to all available source data.

In addition, the AwarenesHub will feature reasoning capabilities to induce the current interruptibility status of MATe users. MATe's reasoners and necessary ontologies are currently under development [24] and will vastly improve the MATe system's usefulness in actual field use.

**DoorPlate.** The DoorPlate is the component which offers the most comprehensive interface to MATe and thus requires special consideration regarding the user interface design. Every team member using MATe has a DoorPlate on his office door. It serves numerous functions: First, it displays the usual information found on door plates, such as room number and the occupant's name. Second, it conveys information about the occupant's current status to visitors, i.e. whether he is present or absent, and, in the former case, whether he agrees to be disturbed by visitors or not. Third, if the person is not interruptible, visitors can leave one of several predefined messages via the DoorPlate's touch screen. Fourth, the occupant of the room can use the touch screen to set his status and view messages in case there are any.

**Desktop PC.** For convenient interaction with the MATe system, users find a desklet on their computer screen. It allows the user to check the current status of his colleagues, set his own interruptibility status, and read and send messages to other users. Basically, the desklet offers the same functionality as the DoorPlate right at the user's workplace. In addition, the user can spawn a web-based interface for setting up the desired information channels and configuring privacy settings, i.e. which colleagues should be able to access which information about his status and current spatial position.

**DropZone.** The DropZone is an ambient frontend to the MATe system, which tracks the presence of users in the room it is installed in (e.g. personal office,

[1] http://xmpp.org/

conference room, laboratory). Users carry a token, and, when entering the room, put this token inside the DropZone. A small software program then reads the token and signals the respective user's presence to the AwarenessHub. There is no back channel. The DropZone is implemented using optical markers in combination with an ordinary consumer-grade web cam.

**Optical Recognition.** Since the DoorPlate is currently based on an embedded ARM platform focused at low electrical power consumption, local computing power is also weak. With regard to the DropZone, computing power is readily available in modern desktop PC systems. But our intention is to keep MATe's impact on the users' usual working routine as low as possible, which includes the performance of their desktop application software. For both reasons, we opted for a server side component for the optical marker recognition.

**Gateways.** Several other services can be accessed via a gateway to the MATe XMPP server. For example, the SMS gateway is a server side component, which is able to send and receive short text messages via the HTTP interface of common HTTP-to-SMS providers. These messages must follow a very simple syntax and may either communicate status changes to the AwarenessHub or request information from it. Incoming text messages are parsed, converted to appropriate XMPP packages, and forwarded to the AwarenessHub, while outgoing XMPP messages are recoded to short natural language sentences and sent to the user's mobile phone. Likewise, the user can communicate with MATe via his instant messaging client.

Our plan is to include other services as well, for communication outwards and as additional sensors. For example, micro blogging sites like Twitter can be used for status updates, or a user's calendar can be accessed via an appropriate protocol. Future planned enhancements include a mail gateway with rudimentary natural language understanding capabilities so that MATe can make use of implicit information contained in mails between co-workers.

### 2.5 Methods

For some time now, our research group has been developing hardware appliances and software systems with which we intend to test our hypotheses as well as develop new ones, and derive design principles for ambient and context aware computer systems. One of these systems has been described in Sect. 2.4 above. Further on, our research group's expertise in alternative user interfaces and interaction devices enables us to try out different ways of communicating the systems' output and reasoning to their users. With several multi-touch tables, 3D projection systems, and a diverse array of wearable devices at hand, we are exploring new representations of our systems' states and processes in a variety of usage contexts.

In addition, besides MATe, several new systems are under development which will further add ambient and contextualized capabilities. In this sense, the research on mental models is a kind of action research: our hypotheses are derived from the existing literature, they are put to the test on existing systems, and adapted to suit the empirical findings. The changed hypotheses will then lead to a revision of our development models, before systems built with the according to changed principles will be tested again to confirm or challenge our reformed hypotheses.

The experimental settings with which we intend to test our hypotheses are designed to fit the MATe system. One of MATe's functions is to convey the user's current interruptibility status to colleagues and visitors, that is, whether it is acceptable to disturb the user. This information will be displayed on the user's DoorPlate, but can also be accessed via Desktop PC applications, by querying the AwarenessHub via the SMS Gateway or an automatically generated Twitter announcement. MATe can obtain the data from which this status information is derived from different sources. These sources can be categorized with regard to the challenges outlined in Sect. 2.1 above.

- A button press in the desktop PC application or on the DoorPlate categorizes as an explicit interaction. The effect of this interaction is also explicit and thus can be looked at with the usual methods of HCI and usability studies.
- Setting one's interruptibility status by taking a muesli bowl to the lunch room is an implicit interaction. It is a voluntary and conscious action, but the user has to learn that it effects his interruptibility status.
- Automatically setting the user's interruptibility status according to his current use of application software on his PC or his typing behavior counts as an implicit interaction. The system's input does not depend on any voluntary and/or conscious action by the user, and the effects of each action by itself are not obvious.

These different interactions will be evaluated with the help of several scenarios. Typical for the use of MATe is the following situation: Alice is in the library reading a paper, while Bob would like to go out for lunch. Usually, he would have to search the institute for several minutes to find Alice in the library. He then would approach her to ask about lunch, thus interrupting her concentration on the paper. With MATe's assistance, Bob will not have to search for Alice, but he will know where to find her after a quick glance at his PC's screen or Alice's DoorPlate. At the same time, MATe will have inferred that because Alice is in the library, but has not typed on her laptop's keybard for some time, she is probably reading and not to be disturbed. Bob can then decide to wait for Alice, to leave without her, or to interrupt her anyway.

Several methods for data collection are currently under evaluation. Since users' mental models are usually complex and difficult to extract (see Sect. 1.2), let alone to interpret and evaluate, research methods suitable to cope with these properties are needed. Established methods from cognitive psychology and usability engineering do not seem to fit our needs because they are created to measure the deviation of the mental model of the user from the conceptual model of the target system. Due to the fact that the system image [19] of a disappearing computer cannot easily delivered by affordances of the user interface the system image has to be actively constructed by the users. Therefore we have to employ methods of elicitating these constructed system images and mental models from the users. This will be done by qualitative user interviews (see, e.g., [1]) and a newly adopted version of the structure-formation-technique by Scheele and Groeben [27] using concept maps (cf. Novak and Cañas [22]) drawn by the users of the MATe system. We plan to collect these data at several times during the prolonged usage of the system in an everyday office context. Besides primary tests at our research group, we will continuously evaluate other options for field tests to ensure that our user base is comprised of persons with different levels of expertise.

### 2.6 Future Enhancements

Although MATe already makes a valuable framework for the empirical testing of our theoretical work and also for the explorative research that helps generate new hypotheses, we plan to extend this framework to include other services and devices which we believe will help us to understand certain aspects of the field better and gain additional data sources for those components that already exist. Since mobile computer systems and thus also mobile human computer interfaces are present in most peoples' lives, we would like to cover mobility and mobility-related computer systems with our framework.

One attempt we are currently making to this end is the adaption of personal navigation and planning appliances to the MATe system. Think of your car being connected to your PDAs calendar application and offering you a pre-planned route to your next appointment. It might even tell your PDAs calendar that it should remind you of the appointment a little earlier than usual, since there is a traffic jam along the way and you need to fill up gasoline anyway. Another interesting service might be to check public transport facilities' time tables and not only propose the best connections, but even buy a ticket online and order a taxi to take you the last mile to your destination.

## 3 Conclusions and Further Work

We have outlined a research program focusing on how mental models of ambient, distributed systems come into being, and how these mental models differ from those arising from interaction with traditional computer systems. Our main axioms are:

1. Mental models can be understood from a perspective which unifies aspects of communication and artifact manipulation of human-computer interaction.
2. Distributed, pervasive, ambient systems and environments pose unique challenges for the development of users' mental models.
3. A better understanding of these challenges can lead to enhanced methods for the development of ambient systems which give better clues for the development of mental models.

Hypotheses about mental models of disappearing computer systems will be generated starting from these axioms. They are put to the test with the help of our research prototypes. We start off with the MATe system. MATe is currently developed to be put into use in a team of knowledge workers to increase awareness about other users' states and interruptibility. We are collecting empirical data about how the users manage interruptibility and their work status in general, and can examine how mental models of the system develop during its use.

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