

HUMAN–COMPUTER INTERACTION IN MOBILE CONTEXT: A COGNITIVE RESOURCES PERSPECTIVE

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Abstract <p>Human-computer interaction is currently shifting its focus from desktop-based interaction to interaction with “beyond the desktop”, which is embedded into everyday activities. In order to support users more elegantly, these mobile, wearable, and ubiquitous computing devices are envisioned to adapt intelligently to their context. Thus far, however, the mobile use contexts per se have received attention, as most research has been technology-driven. Drawing from cognitive psychology, user modeling in human-computer interaction, and ethnomethodology, a framework is put forward here to analyse mobile use situations from the point of view of resource competition. The framework assumes that mobility is inherently multitasking and easily leads to competition for cognitive and other human resources. This “cognitive resource competition” framework is elaborated and associated with the psychological principles of capacity and multitasking. It looks at the typical social, interactional, cognitive, and physical tasks in mobility, relates them to the typical cognitive resources they compete for, and, based on known capacities of cognitive faculties, pinpoints restrictions and resources for action that can emerge in a given mobile situation. It is argued that the approach is useful for identifying the perceptual, attentional, and cognitive capabilities of a user in a mobile situation. The approach has implications for the design and innovation of intelligent, context-sensitive user interfaces and services. Furthermore, a practical method for making human resources visible in a design session is proposed and evaluated.</p>		
Keywords Mobility, context-awareness, human-computer interaction, cognitive psychology, ethnomethodology, user modeling, attention, memory, central capacity		
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Helsingin yliopisto
Käyttätymistieteellinen tiedekunta

Lausunto Antti Oulasvirran kognitiotieteen lisensiaattitutkimuksesta "Human-Computer Interaction in Mobile Context: A Cognitive Resources Perspective"

Antti Oulasvirta tarttuu kognitiotieteen lisensiaattityössään "Human-Computer Interaction in Mobile Context: A Cognitive Resources Perspective" mielenkiintoisella tavalla kognitiotieteellisesti ajankohtaiseen ihminen-tietokone-vuorovaikutus – tutkimusalueen teemaan kuitenkin tukeutuen varsin vahvasti perinteikkääseen tarkastelunäkökulmaan. Oulasvirran valitsema teema mobiileista käyttötilanteista, konteksteista, on HCI-tutkimuksessa erittäin ajankohtainen. Tutkimusalueen tämän vuoden pääkonferenssissa CHI'2004 aihe onkin yhtenä keskeisimmistä teema-alueista. Oulasvirran neljäs lisensiaattityössä mukana oleva julkaisu onkin ollut esillä yhdessä tämän arvostetun konferenssin työpajoista.

Ajankohtaisuudesta huolimatta Oulasvirran tutkimusteeman valinnalla on perinteikkyyttä. Hän nostaa työssään esiin 1980-luvun alkupuolelle juontavat juuret käyttäjän toiminnan kognitiiviseen mallittamiseen (Card, Moran), jonka voidaan jopa katsoa olleen HCI-alueen päälinja tuolloin. Nytemmin tämä tutkimuslinja on yhtenä osa-alueena muun tyyppisten tutkimusotteiden löydettyä myös tiensä monitieteisen HCI-tutkimuksen piiriin. Oulasvirran työn taustalla vaikuttaakin itse asiassa yksi tällainen - etnografinen tutkimus- ja suunnitteluote (mm. Beyer & Holzblatt), joka ilmenee kahdesta ensimmäisestä Oulasvirran työssä olevasta artikkelista. Kontekstittietoisuutta tarkasteltaessa myös teknispainotteinen suunta on Oulasvirran työssä tunnistettu asianmukaisesti (Schilit, Abowd, Dey, Tennenhouse).

Oulasvirran työn yhteenveto-osuus on rakenteeltaan varsin selkeä. Yhteenvedon johdannossa (luku 1) tunnistetaan tutkimuskenttä ja teema-alue, jolla työssä esitettävä tutkimus on relevanttia. Yhteenveto-osuuden toisessa luvussa tarkennutaan tutkijan oman tutkimusaiheen käsitteistöön ja sen erityispiirteisiin. Kolmannessa luvussa esitellään työhön kuuluvat tieteelliset artikkelit ja viimeisessä luvussa (luku 4) esitetään pohdintaa havaintojen merkityksestä ja hahmotellaan edellytyksiä jatkotutkimukselle.

Tulevaisuutta ajatellen Oulasvirta voi nostaa työssään hahmottelemansa viitekehityksen "cognitive resources competition framework" painoarvoa ja näkyvyyttä keskeisenä työn tuloksena. Mallin selkeämpi ja terävämpi esittely omana kokonaisuutena jatkotyössä olisikin tärkeää. Oulasvirran tuottama malli ja käsitejäsenitys on asia, joka tarjoaa uutta tietoa valitulle akateemiselle teema-alueelle. Työssä on myös tunnistettu, että jatkotutkimusta olisi tarpeen tehdä mm. kehitetyn mallin evaluoimiseksi. Tällä täydennyksellä Oulasvirran hahmottelema käsitteellinen malli

saisikin vankan perustan jatkossa tapahtuvan kognitiotieteellisen tutkimuksen ja soveltamisen pohjaksi.

Oulasvirran työssä mukana olevat artikkelit on julkaistu HCI-tutkimuksen näkökulmasta asianmukaisilla foorumeilla. Foorumit ovat suhteellisen nuoria, mutta tämä on ymmärrettävää teema-alueen uutuuden ja ajankohtaisuuden kautta erittäin hyvin. Kaksi aikakausjulkaisussa julkaistua (toinen hyväksytty julkaistavaksi) artikkelia, yksi konferenssipaperi ja yksi työpajapaperi pääkonferenssissamme on lisensiaatintyölle vähintäänkin riittävää. Sikäli, kun työpajapaperista on mahdollisuus saada julkaistuksi tieteellinen aikakauslehtiartikkeli, työn laajuus, laatu ja painokkuus alkaa jo hyvinkin lähestyä väitöskirjaa.

Paitsi että Oulasvirran työ tarjoaa hyvät puitteet tutkijalle itselleen jatkotutkimukseen, se toimii erittäin hyvänä tutkimusaluetta kartoittavana lähdeluettelona ja käsitteenjäsennyksenä myös muille aihealueella työtään tekeville tutkijoille. Oulasvirran työ on ansioillaan sellaisella tasolla, että tutkijan itsensäkin jo tunnistamalla suhteellisen pienillä täydennyksillä ja terävöinneillä työstä on aikaansaataavissa väitöskirja, jota lämpimästi suosittelemme tämän työn pohjalta tehtäväksi.

Esitämme, että Antti Oulasvirran kognitiotieteen lisensiaatintyö hyväksytään arvosanalla "kiittäen hyväksytty".

Helsingissä, 3.5. 2004


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LIST OF ORIGINAL PUBLICATIONS

This thesis consists of a summary and four papers. The publications, presented below with abstracts and descriptions of the author's contribution, are referred to in the text by their Roman numerals **I-IV**. The two first ones have been or are going to be published in a recognized international journal, the third one in a high quality peer-reviewed international conference, and the fourth one in a peer-reviewed international workshop in a high quality conference.

I Oulasvirta, A., Kurvinen, E., & Kankainen, T. (2003). Understanding contexts by being there: Case studies in Bodystorming. *Personal and Ubiquitous Computing* 7 (5), 125-134.

Abstract. A thorough appreciation of physical, social, interactional, and psychological contextual factors is crucial in the design of ubiquitous computing applications. This paper investigates the benefits of a method, called bodystorming, for carrying out design sessions in the original context, "in the wild", instead of the office. A location is selected that is identical or similar to the original environment. Innovation, carried out on-site, is based on ethnographical data presented as concrete design questions. Individual solutions to design questions are brainstormed and discussed on-site. Facets of data collection and preparation, formulation of design questions, selection of locations, session administration, and evaluation of design ideas are presented. We found that bodystorming permits immediate feedback for generated design ideas and can provide a more accurate understanding of contextual factors. Bodystorming sessions were found memorable and inspiring. It is best suitable for designing for activities that are accessible and unfamiliar to the researchers.

As the first author, Antti Oulasvirta has, together with co-authors, designed and conducted the experiment. He has carried out the evaluation of results and written most parts of problem setting, motivation, and discussion.

II Tamminen, S., Oulasvirta, A., Toiskallio, K., & Kankainen, A. (accepted). Understanding mobile contexts. Accepted for publication in *Personal and Ubiquitous Computing*, Springer-Verlag.

Abstract. Mobile urban environments present a challenge for context-aware computers, because they differ from static indoor contexts such as offices, meeting rooms, and lecture halls in many important ways. Internal factors such as tasks and goals are different—external factors such as social resources are dynamic and unpredictable. An empirical, user-centered approach is needed to understand mobile contexts. In this paper we present insights from an ethnomethodologically inspired study of 25 adult urbanites in Helsinki. The results describe typical phenomena in mobility: how situational and planned acts intermesh in navigation, how people construct personal and group spaces, and how temporal tensions develop and dissolve. Furthermore, we provide examples of social solutions to navigation problems, examine mobile multitasking, and consider design implications for context-aware computing.

Antti Oulasvirta's contribution to this article is the cognitive and design implications of the found phenomena. He has contributed significantly also to carrying out the research and writing the problem setting and motivation parts of the paper.

III Kurvinen, E., & Oulasvirta, A. (in press). Towards socially aware pervasive computing: a turntaking approach. Accepted to *2nd International IEEE Conference on Pervasive Computing and Communications*, Orlando, Florida, March 2004.

Abstract. Social context is an important yet an under-researched area in context-sensitive computing. This paper adopts a framework from social sciences that views social context as a sequence of turns taken between participants. The approach is illustrated and evaluated through three empirical cases. The results show that social context is not a static and passive surrounding of a device, but dynamic and constructed by people. Challenges and restrictions for modeling social context through turntaking are identified.

As the second author, Antti Oulasvirta has written main parts of the problem setting, motivation, and discussion sections. Moreover, he has participated in the collection of data.

IV Oulasvirta, A., & Tamminen, S. (accepted). Temporal tensions and human–computer interaction. Accepted for publication in *the proceedings of CHI2004 Workshop on Temporal Aspects of Work*. An extended version tentatively invited, by the workshop chairs, for the journal *Human–Computer Interaction*.

Abstract. The need to understand how temporal factors shape work and interaction has been acknowledged. This position paper presents the notion of temporal tension: time is seen as the subjectively felt tension between the task deadline and the current speed or pace of work. Five tensions of time are distinguished: acceleration, balance, hurrying, deceleration, and waiting—all associated with different cognitive and social factors relevant to interaction. We discuss how these temporal tensions could and have been taken into account in the design of interactive systems.

As the first author, Antti Oulasvirta has significantly participated in the writing of the paper, excluding only the definition of ethnomethodology, social scientific characterization of temporal tensions, and some parts in the discussion on the models and concepts of contexts.

PREFACE

The research presented in this Licentiate Thesis has been carried out in the User Experience Research Group (UERG), working at the Helsinki Institute for Information Technology (HIIT). Formed in 2000, the strategy of UERG has been to investigate potentials in everyday lives of normal people (not just researchers or businessmen) for future technologies, especially in areas where Finnish IT industry has or may reach a significant global role. UERG aims to complement research in industry by studying the psychological, social, and ethical aspects of technology.

The research presented here is part of a larger enterprise investigating use potentials for future technologies by human-centered methodologies. The human-centered research framework utilized at UERG takes as the starting point societal demands and individual human needs, and proposes methods for discovering them (Kankainen & Oulasvirta, 2003; Kankainen, 2003; Oulasvirta, Tiitta, & Saariluoma, 2002; Oulasvirta, 2003, 2004). The *humanistic research strategy* (Oulasvirta, 2004) believes in human rationality, creativity, and morality, and recognizes that human values have their source in experience and culture. It emphasizes that all people have ability to lead meaningful lives. People acquire purpose in life through developing talents and using them for the service of humanity. This ideal is here translated into three guiding research goals:

- *Relevance*. Design must aim to address problems or needs that are relevant to people. Explicating the relevance is important early on in design, as it legitimates it and guides it.
- *Understanding*. All design must be based on a holistic (meaning: including their psychological, social, and ethical aspects) understanding of people and their activities.
- *Empowerment*. The objective in design is to provide tools and services that empower and enable people themselves to address their social, rational, and emotional needs. Equality, autonomy, and control are the goals of empowering design.

The strength of the humanistic strategy is that it functions as “glue” that binds together different stages of design. Grounding innovation to simple ethical principles provides starting points for looking at societal and individual demands for novel technologies, helps to focus empirical studies to relevant human and contextual aspects, guides design in the form of simple goals, and structures evaluation of ideas. Moreover, it helps to recognize scenarios where a proposed technology or interaction style does not address any relevant need or where the need could be satisfied more easily by other means. However, in comparison to the technology-driven approach, it comes with a price, as it requires time-consuming empirical studies and an ability to explicate, track, and rationalize design goals at all stages of design. The present thesis must be understood within the context of this larger enterprise.

During the time of the research presented in this Thesis, UERG has consisted of Dr. Martti Mäntylä, professor on leave from Chair of Information Technology at the Helsinki University of Technology, Dr. Timo Saari, a media psychologists and director of research at the Center for Knowledge and Innovation Research, postgraduate and later on Dr. Anu Kankainen, psychologist and researcher of user-centred methodologies in innovation of design concepts, postgraduate Esko Kurvinen, conversation analyst and industrial designer, MSc and ID Tomi Kankainen, researcher

of evaluation of product concepts, MA Sauli Tiitta, usability and user research practitioner, MSc Jyrki Oraskari, ubiquitous and mobile technology engineer, MSc Tancred Lindholm, middleware researcher, MSc Matti Rantanen, researcher of user modeling in ubiquitous computing, postgraduate and later on Dr. Jan Blom, researcher of personalization, and MSc Antti Salovaara, researcher of proactive computing and user-centered methods.

I am indebted for all the current and past members of UERG for inspiring and energetic atmosphere. Especially, I want to mention Esko Kurvinen and Tomi Kankainen for having trust on me when the first draft of the Bodystorming paper was rejected, Anu Kankainen for her expert guidance in writing the Understanding Mobile Context paper, professors Pertti Saariluoma and Martti Mäntylä for providing practical support, Sakari Tamminen and Kalle Toiskallio for their social scientific input, Giulio Iacucci for useful references, and Antti Salovaara and Jan Blom for lively discussions and commenting on my work. As co-authors writing the three papers, Sakari, Esko, Tomi, Anu, and Kalle have all been energetic, supportive, and enthusiastic; in other words, good people to work with. My ethnomethodologically oriented colleagues, Sakari Tamminen, Esko Kurvinen, and Antti Salovaara, deserve a special recognition for sparking off the ideas behind this thesis. Furthermore, I want to thank Pertti Saariluoma for teaching me the kind of critical and innovative thinking that is required to survive in a fluctuating, multifaceted, controversial field like the field of human-computer interaction is at the present.

During the past two years, I have been financially supported by Helsinki Institute for Information Technology (my current employer) and the industrial partners of the Between project (Alma Media, Elisa Communications, Nokia, Sonera, Swelcom). My visit to the Department of Psychology at the University of California, Berkeley, was generously supported by TKK:n tukisäätiö, Elisan säätiö, Academy of Finland, and University of Helsinki. I am thankful for this generous support.

Finally, special thanks are reserved for Lennu.

Antti Oulasvirta
Helsinki, March 2004

"Inspired by the social scientists, philosophers, and anthropologists at PARC, we have been trying to take a radical look at what computing and networking ought to be like. We believe that people live through their practices and tacit knowledge so that the most powerful things are those that are effectively invisible in use. This is a challenge that affects all of computer science. Our preliminary approach: Activate the world. Provide hundreds of wireless computing devices per person per office, of all scales (from 1-inch displays to wall sized). This has required new work in operating systems, user interfaces, networks, wireless, displays, and many other areas. We call our work 'ubiquitous computing'. This is different from PDA's, dynabooks, or information at your fingertips. It is invisible, everywhere computing that does not live on a personal device of any sort, but is in the woodwork everywhere."

Mark Weiser

1 INTRODUCTION

Mark Weiser, widely acknowledged as the father of ubiquitous computing, envisioned in the beginning of 1990s that *ubiquitous computing*, intelligent small-scale technology embedded in the physical environment, would provide useful services in the everyday context of people where they were needed, without disturbing the natural flow of human activities. The technology would "fade into the background", the woodwork and fabric of everyday life, and incorporate what he called "natural user interfaces". (Weiser, 1991.)

Quickly after Weiser's vision, the idea was adopted from ubiquitous to personal technologies—mobile and wearable computing (e.g., Abowd *et al.*, 1997; Long *et al.*, 1996; Schilit *et al.*, 1994). Together, contextual intelligence in ubiquitous, wearable, and mobile computers is here called *context-awareness*. Context-aware devices are supposed to monitor the changing contexts of the user and adapt appropriately through interpreters, aggregators, and services. Thus, context-awareness refers to the ability of a device to gather and interpret contextual information from its environment, and use it for the benefit of the user (Dey, 2001; Schmidt & Laerhoven, 2001). Context-aware services and user interface adaptation are the two main classes of application for context-awareness. Many recent prototypes demonstrate how context-aware devices might be used in homes, lecture halls, gardens, schools, city streets, cards, buses, trams, shops, malls etc—in other words, elsewhere than at the desktop.

Technology-wise, this vision is based on recent advances in hardware and software technologies. Processors, memories, wireless networking, sensors, actuators, power, packing and integration, optoelectronics, and biomaterials have seen rapid increase in efficiency with simultaneous decreases in size. Moore's law on capacity of microchips doubling every 18 months and growing an order of magnitude every 5 years has been more or less accurate for

the last three decades. Similarly, fixed network transfer capacity grows an order of magnitude every three years, wireless network transfer capacity every 5-10 years, and mass storage every 3 years. Significant progress in power consumption is less likely, however. Innovations and breakthroughs in distributed operating environments, ad hoc networking, middleware, platform technologies, and user interfaces have recently begun to add to the software-side of the vision. Examples of innovations in input and output technologies, as they are mostly relevant here, are illustrated in Figures 1 and 2, respectively. (Marti Mäntylä, personal communication; Satanarayan, 2001; Tennenhouse, 2000.)

However, despite the millions of euros spent on context-awareness research, there are hardly any successful products in the mass consumer market. Consequently, pessimists have said that the only truly useful context-aware application, the automatic door, has been already invented decades ago. Partly because some of the promising ideas have not been technologically feasible, but partly because design and innovation have been unsystematic and based on intuition, we still remain to see the “killer application” of context-awareness.

The belief motivating the present work is that, if adequately informed by cognitive and other human sciences, context-aware computing can and will find its niche in human lives. Context-aware computers need “awareness” of several contextual factors such as the social, psychological, physical and the like. What are these factors, and how they should be interpreted and acted upon, is the question addressed in this research.

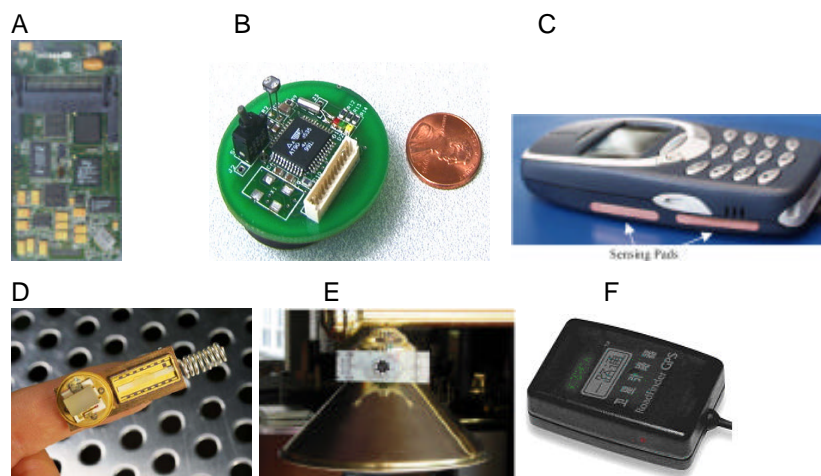


Figure 1. Examples of sensor technologies: A) A matchbox-sized integrated sensor board, including sensors for audio, acceleration, temperature, humidity, light, and infrared (HP/KTH SmartBadge, Smith & Maguire, 2004); B) A coin-sized integrated board for light and temperature sensing (Berkeley Smart Dust); C) Pads for sensing tactile contact with a mobile cell phone investigated at VTT and Nokia; D) Siemens’ fingertip-sized standalone pressure sensor; E) Light fixture with eye contact sensor (Vertegaal, 2003); F) A matchbox-sized GPS for 1 meter accurate outdoor location sensing.

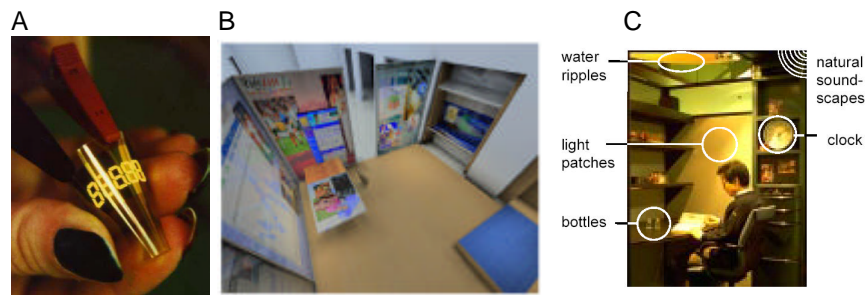


Figure 2. Examples of output technologies: A) 1mm thick flexible plastic displays for tangible user interfaces; B) large shared displays for public and semi-public places (Intille, 2001); C) ambient media for office spaces (Ishii & Ullmer, 1997).

1.1 The Field of Context-Awareness is in a Contradictory State

"Ubiquitous computing names the third wave in computing, just now beginning. First were mainframes, each shared by lots of people. Now we are in the personal computing era, person and machine staring uneasily at each other across the desktop. Next comes ubiquitous computing, or the age of calm technology, when technology recedes into the background of our lives."

Mark Weiser

Whereas the vision of "third paradigm computing" has innovated numerous technological advances, the human-oriented branch within human-computer interaction (HCI) has lagged behind. Numerous visions of *how* the new context-aware technology is going to be used, and what *for*, have been put forward by prominent researchers, without a consensus in the horizon. The new kind of interaction has been proposed to be more physical, engaging, and tangible (e.g., Ishii & Ullmer, 1997), but at the same time more natural and implicit (Schmidt, 2000). It has also been thought to provide resources for spontaneous user-initiated action (Kindberg, 2003), whereas others think it should be proactive (Tennenhouse, 2000). The idea of pervasive computing, "access to information anywhere, any time" (e.g., Satyanarayanan, 2001), has been criticized, and asynchronous interaction that leaves more room for reflective cognition has been called for (Jones *et al.*, 2003). At least 15 different terms have been put out to describe the relationship of the new technology to users, services, or environment. Consider, for example, proactive, ubiquitous, pervasive, mobile, situated, wearable, ensemble, invisible, context-aware, peripheral, and calm computing, ambient intelligence, disappearing computer, attentive and intelligent user interfaces, and personal technologies, each having their proponents.

To get a grasp of the contradictory state, consider the following enterprises: (adopted from Oulasvirta & Salovaara, 2004):

- *Perceptual invisibility*. According to an interpretation of Weiser championed by Philips (as cited by Tolmie *et al.*, 2002), computers at the age of ubiquitous computing should be invisible. Weiser's "disappearance" is here taken literally to mean perceptual invisibility.
- In *Peripheral Computing*, the interface attempts to provide peripheral awareness of people and events. Ambient channels provide a steady a flow of auditory cues (such as a sound like a rain) or gradually changing lighting conditions (e.g. Ambient Media by Ishii & Ullmer, 1997).
- *Tangible Bits*. Similarly, According to Ishii, "The smooth transition of users' focus of attention between background and foreground using ambient media and graspable objects is a key challenge of Tangible Bits" (Ishii & Ullmer, 1997).
- The idea in *Multimodal Interfaces* is to use unreserved modalities for interaction. This calls for understanding what modalities are typically reserved in a use situation (e.g., Sawhney & Schmandt, 2000).
- *Attentive User Interfaces* (AUIs) are based on the idea that modeling the deployment of user attention and task preferences is the key for minimizing the disruptive effects of interruptions. By monitoring users' physical proximity, body orientation, eye fixations, and the like, AUIs can determine what device, person, or task the user is attending to. Knowing the focus of attention makes it possible in some situations to avoid interrupting users in tasks that are more important or time-critical than the one interrupting. (E.g., Vertegaal, 2003.)
- In *Unremarkable Computing*, the focus is on designing domestic devices that are "unremarkable" to users. Here, invisibility is understood as the use of a device being a *part of a routine*, since "routines are invisible in use for those who are involved in them" (Tolmie *et al.*, 2002: p. 403). Then, technology is subservient to routines and actions: "...the key point is that the computation is in service of actions – everyday actions – which themselves have a significance" (p. 404).
- *Proactive Computing* was recently introduced by Tennenhouse (2000) and colleagues. The enabling technologies include sensors and actuators intimately connected to the physical world, processors with faster-than-human operating speed, and autonomous software programs assembled to form "knowbots" assigned for helping the user. The key idea is using simulations of the real world to make inferences and predictions that

anticipate and prepare for events. User's role in a proactive system is to monitor and steer processes, without actively intervening in decision-making situations that may arise. The user is relieved from making decisions every time when the system encounters a branching point in its activity.

- A somewhat similar approach that also attempts to delegate decision-making responsibility to intelligent systems is taken by the *Ambient Intelligence* (AmI) technology programme of the European Union (ISTAG). One part of the AmI vision entails intelligent agents that assume some of the control responsibility from users.

In brief, the context-awareness research can be said to be in a contradictory state, or in a state of anomaly in Kuhnian terms.

1.2 Mobile Use Contexts are the Challenge

"The coherence of situated action is tied in essential ways not to individual predispositions or conventional rules but to local interactions contingent on the actor's particular circumstances."

Suchman (1987: p. 28)

The characteristic feature of interaction with context-aware computers is that it typically takes place while being away from the desktop. Some researchers call the paradigm "technology beyond the desktop" (Bellotti & Bly, 1996). The hypothesis advocated here is that the core of the problem of context-aware HCI has been that use contexts of the desktop-based computing are radically different from the use context of context-aware computers. The concepts and theories we talk about HCI have been conceptually inadequate; in other words, weak from the point of view of explanatory power.

Mobile contexts differ from desktop-contexts: internal factors such as tasks, needs, and goals are different, as are external factors such as social resources and present objects and events (Figure 3). Indeed, when data from our mobility data (Paper II, Kankainen & Oulasvirta, 2002; Oulasvirta, 2004) were classified, shopping, evaluating people, selecting routes, ad hoc meetings, SMS messaging, relaxing, waiting, surprising and delighting others, rendezvousing, being late, safety, acquiring information, collecting memories, and gags were among the most frequent, in contrast to "desktop contexts". Moreover, mobile contexts encompass larger geographical area for movement, involve many unidentifiable users and devices, loosely defined leisure oriented tasks, dynamic environment and objects, more interruptions and disrupting stimuli etc. Therefore, new conceptual approaches are needed for describing, explaining, and predicting human behavior in mobile contexts.

What, then, are the characteristic features of “the mobile context”, becomes the overarching question for researchers. Three closely related questions emerge from the interests of the three main stakeholders in this research enterprise:

- *Social science*: What are the relevant (for the user) contextual factors and resources in mobile use situations and user activities?
- *Psychology*: How can the context be used to support the user, without distracting the original on-going tasks and activities?
- *Computer science*: What are the context sensors that can recognize these meaningful contexts and, moreover, help discriminating among them?

To date, hardly anyone seems to have paid attention to the two first vital questions, although millions of euros have been spent every year for the technology side of the enterprise (Thackara, 2001). A recent meta-review of empirical work in mobile HCI echoes this claim (Kjeldskov & Graham, 2003).

1.3 The Concept of Context is Being Elaborated

Early research in context-awareness can be characterized as an attempt in finding universal context attributes that would be needed for many (or all) ubiquitous computing applications (Dey, 2001; Pascoe *et al*, 1998; Schmidt & Laerhoven, 2001). Some attributes, such as location and time, were indeed repeatedly found important for many applications. Starting from this “general definition” point of view, it has been found difficult to introduce new technology into the rich fabric of everyday human lives. Mobile contexts have proved to be too surprising and complex for an armchair-based analysis.

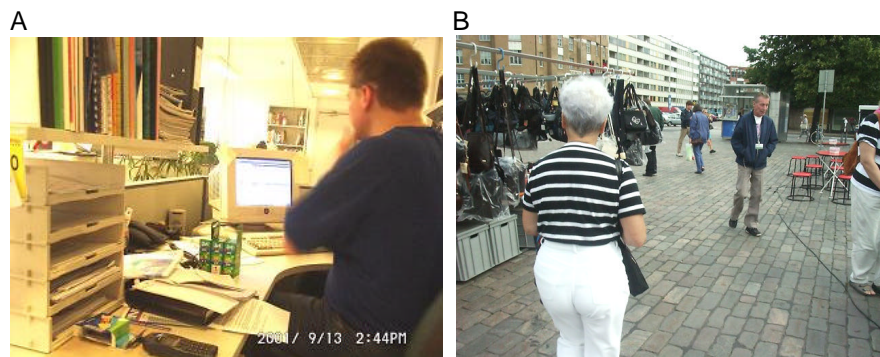


Figure 3. Situational and factors affecting human–computer interaction in an A) office and in B) mobility differ radically. Internal factors such as tasks and goals are different—external factors such as social resources are dynamic and unpredictable.

Consequently, however, many researchers are beginning to agree that a more worthwhile approach is to determine the contextual attributes for each application individually. It has been recognized that the overarching goal in the design of any “in the wild” interactive system is, then, to discover the *specific* physical, social, interactional, and/or psychological factors important in making the flow of interaction natural in a particular context (e.g. see *Personal and Ubiquitous Computing 5* or *Human-Computer Interaction Vol 16*). This kind of research, reviewed briefly below, has begun to emerge only very recently.

The main assumption underlying this research has been that the only way to inform the design context-aware interactive systems is through empirical work guided by a theory. Only this kind of research can uncork “the mobile context” by describing, explaining, and ultimately predicting mobile human behavior.

1.4 Previous Empirical Research

Most of the earliest empirical research on mobility dealt with purely technology issues such as limited battery life, unreliable network connections, risk of data loss, portability and location discovery (see Wiberg and Ljungberg, 1999). Technological advances have largely driven this branch of research. The viewpoint of the end users was ignored.

The majority of the first boom in empirical research of mobility, timed around 1999, concerned fixed indoor contexts (e.g., offices, meeting rooms, and lecture halls). Maybe because of the apparently static nature of such settings, the research tried to create rigid taxonomies and general “all-embracing” definitions of context—with a negligible success. Much of this literature still characterized mobility as flexible geographical movement of people (e.g. Makimoto and Manners, 1997; Dahlbom and Ljungberg, 1998; Fagrell *et al.*, 1999; Kopomaa, 2000).

Soon afterwards, as discussed above, the concept of context has changed towards social sciences. When, quite recently, such research has been carried out in a more human-centered way, the focus of studies has been on different kinds of *work contexts* and *mobile workers*. For example, Luff and Heath’s (1998) analysis of different kind of mobilities and their relation to collaborative work together with Perry *et al.*’s (2001) study of the everyday nature of mobile businessmen’s work pointed out several problems and possibilities relating to mobility and mobile contexts. Perry *et al.* (2001) studied mobile workers and found that mobility requires planning information access (e.g., taking folders with you when from work), triggers new

habits and possibilities of working in dead time (e.g., calling colleagues to make appointments), enables access to remote technological and informational resources, leads to using mobile phone as a proxy (i.e., mobile phone is used to replace some of the usual means for achieving goals, for example remote awareness of colleagues).

Within the new social scientific approach, mobility has now been seen more broadly as a requirement for accessing *resources* that are not available at the desktop context. Mostly these resources are to do with the people and artefacts of the environment. Bellotti and Bly (1996) agree that mobility is essential for shared resources and for communication. Mobile people are in pursuit of resources and other people. Nelson *et al.* (2001) showed that the social context—norms, roles, and social pressure in their case—can suppress and trigger these mobile resources. For example, they observed how people had to talk quietly, move the conversation elsewhere, do not take the call, or use alternative channels (e.g., SMS) when trying to communicate private issues over a mobile phone in a public place.

The cognitively oriented approach is represented only in the work of Kristoffersen and Ljungberg (1999). They note that resources in mobility are reserved to a large extent for other activities than interaction, visual attention especially, but are not able to relate this analysis to research or theories in cognitive sciences. Instead, they are looking solely at the resources the user has for interaction, not environmental or task-related resources, or the interplay of those, as done in this thesis. Their findings on how mobility restricts resources, consequently, render to quite trivial observations of people's resources in mobility. First, they notice that, often, there's no place to put the device down when there's a need to do something else. Secondly, when hands are taken by another task, mobile interaction becomes impossible. Third, visual attention is reserved to a large extend for mobility, not interaction.

"the definition of cognition has been unhooked from interaction with the world"
Hutchins (1995: p. 367)

2 THE RESOURCE COMPETITION APPROACH

The approach presented in this thesis borrows the idea of looking at different resources from Kristoffersen and Ljungberg (1999). However, the idea is conceptually refined and extended towards cognitive sciences. This framework was inspired by work of Navon (1984, 1985) on the resource approach to attention. As it now stands, it comes closer to the established tradition of cognitive modeling in traditional HCI, stemming from the pioneering work of Card, Moran, and Newell (1983), and later elaborated by Kieras and Meyer (1997), J.R. Anderson (1983; Byrne, 2001) and many others. These computational models have modeled cognitive faculties in interaction tasks such as selecting a menu item, interpreting spreadsheets, writing a piece of code and the like.

The approach proposed here does not aim for *modeling* the interplay of cognitive faculties, only *describing* how multitasking leads to competition from their resources. The aim of the present framework is to gain a general understanding of the determinants of human behavior in mobile contexts (Landauer, 1997). If successful, it can be used to analyze and solve HCI problems in mobile use contexts.

2.1 Assumptions

The following assumptions are made in the resource competition approach:

- *Functional modularity.* Human cognitive system is divided into functionally separate subsystems operating on different mental representations at different levels of mental processing (Fodor, 1983).
- *Parallel module operation.* Cognitive modules can operate to a large extent in parallel independently of each other, although structural interference can occur.
- *Serial central operation.* Central co-ordination of modules (monitoring, manipulation, information transfer among them, and response selection) is inherently serial (Broadbent, 1958; Pashler, 1993).

- *Capacity-limitations.* Cognitive modules are limited in capacity, either regarding to time (e.g., long-term memory) or content (e.g., perception), or both (e.g., working memory). (Broadbent, 1958; Cowan, 2001; Cherry, 1953; Kahneman, 1973; Miller, 1956; Schneider & Shiffrin, 1977.)

These first four assumptions define what is comprehended as “resource” here. The last five assumptions define the “competition” part of the approach:

- *Multitasking.* At any time, multiple tasks are to be performed by the cognitive machinery.
- *Resource pooling.* All operated tasks share and compete for the limited resource pool (Kahneman, 1973; Navon, 1984, 1985.)
- *Task differences.* Different tasks reserve different quantities of different cognitive resources.
- *Preferential resource sharing.* Resources are not assigned for tasks equally but preferentially according to intrinsic motivations, needs, goals, and the like (e.g., Deci & Ryan, 1985).
- *Resource-depletion penalty.* Tasks that are denied resources are slowed-down, postponed and put on hold, or stopped completely (Baddeley & Hitch, 1974; Ericsson & Kintsch, 1995; Welford, 1952).

Table 1 presents some of the main cognitive and action resources that the competition is *for*.

2.2 Investigating Mobile Multitasking

To crystallize the idea of resource competition, it can be summarized as follows. As the mobile use contexts involve many sequentially and simultaneously performed tasks, they can be called *multitasking contexts*. This is the most prominent distinction to the work done with desktop-based computing that does not look at multitasking at all but concentrates on maximum (and worst) performance on one task performed at a time (e.g., Byrne, 2001; Card *et al.*, 1984; Kieras & Meyer, 1997). The starting point here, by contrast, is that frequent task-switching is an unavoidable implication of multitasking and our cognitive limitations. Because the cognitive resources are limited, we must switch back and forth between tasks and information sources, leaving the switched-from tasks temporarily on hold or slowing them down. Successful multitasking is a complex cognitive achievement, requiring planning, timing,

monitoring, and control of action. Resource competition leads to this achievement breaking down. When demands are too high, errors in this process occur, inevitably.

The approach calls for looking at the cognitive and other demands of a situation to see the possible resource competitions and consequences for interaction, as presented in the examples of Table 1.

Table 1. Cognitive faculties, provided resources, limitations, and practical examples.

COGNITIVE FACULTY	PROVIDED RESOURCES	LIMITATIONS	EXAMPLES OF RESOURCE FAILURES IN MOBILITY
Sensation	Intake of external stimuli	Acuity, accuracy	Not being able to read a distant road sign
Perception	Organization of sense datum	Only one interpretation at a time	Misperceiving a tactile stimulus from a mobile device to be part of environmental shattering
Attention -visual -auditory -motor	Modality-bound search and selection, and integration of stimulus materials	Limited spatial and object-bound span	Attending unimportant sources of information and missing important ones (e.g., not noticing another person's non-verbal behavior). Attentional capture during an important task.
Central executive	Control of cognitive operations -Selection -Inhibition -Updating -Shifting	Serial processing	Wrongly timed attention-switch causes an omission in another task
Working memory -Visual subsystem -Auditory subsystem -Motor subsystem	Retention of previously attended information Modality-bound subsystems	Short retention time Small capacity Conscious control	Externally triggered interruption leads to forgetting a task goal
Thought	Meta-level control Higher-level manipulation of information -abstraction -inference -reasoning -problem-solving	Uniformity of thought Reliance on fast but frugal heuristics	Choosing a non-optimal or wrong route. Failing to notice a latent error in route selection.
Prospective memory	Proactive control of action	Susceptible to interference	Pushing a stop button in bus at a familiar-but-wrong time
Episodic memory	"Mental time travel"	Distortions, slow and effortful access	Misremembering a navigation route
Semantic memory	Fact knowledge	Susceptibility to interference	Remembering a wrong address
Motor control	Sequencing and timing of motor operations based on motor skills	Dependent on well-learned automatized schemata	Complex motor tasks requires all attentional resources
(Hands)	(Manipulation of objects)	(Limited reach, capacity, strenght, accuracy, and dexterity)	(Inaccurate manipulation of mobile device)
(Legs)	(Positioning the Self to the external world)	(Limited speed)	(Missing a bus due to slow walking speed)

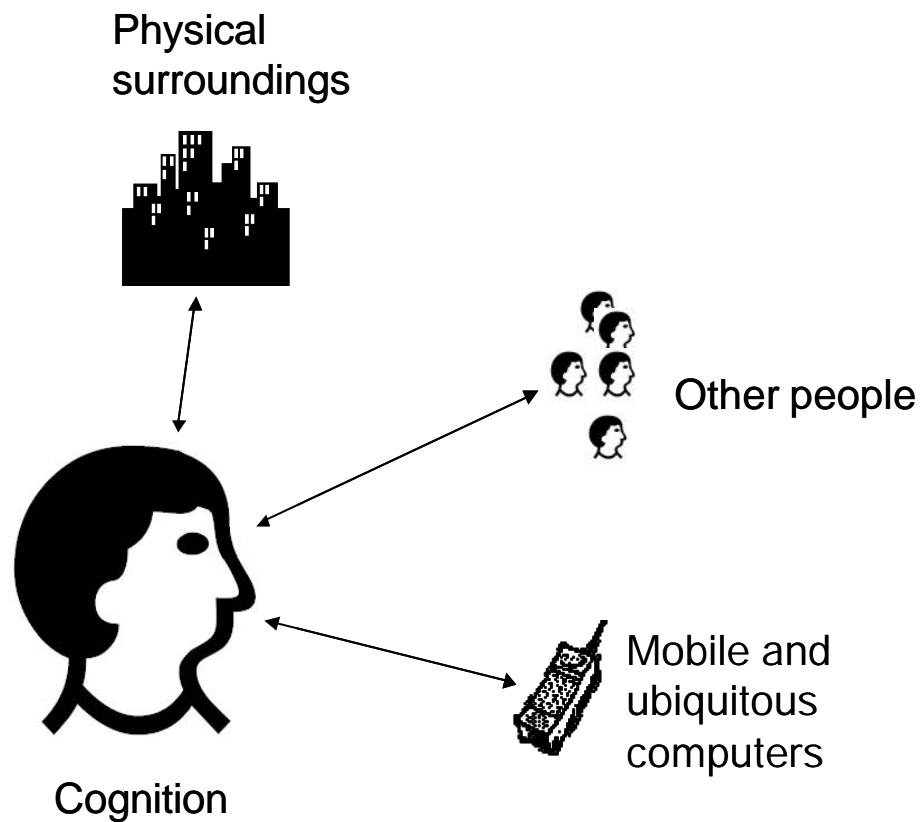


Figure 4. Three classes of tasks in mobility. The user must share her resources among tasks that relate to physical surroundings, other people, and present computing devices.

A starting point is taken according to which that three categories of tasks compete for these resources: those related to physical surroundings, other people, and computers. Figure 4 presents this position. If we can analyze the typical resource demands of typical tasks carried out in mobility, we can predict the kind of resource limitations that are carried over for interaction with mobile devices. This idea is in contrast to research in traditional desktop-based interaction that has mostly looked at tasks related to computers.

3 OVERVIEW OF ARTICLES

This chapter summarizes the starting points, methods, and findings of the four papers. Discussion of the contribution of the approach as a whole is postponed to the next chapter.

3.1 Paper I: Bringing the Design Session “into the Wild”

Ultimately, we, as HCI researchers working in the field of context-awareness, are interested in designing more intelligent mobile human-computer interaction—intelligent in the sense that it is more sensitive to those aspects of its use contexts that have implications for interaction. The first part of the present thesis has looked at bringing the design team into the wild. The recognized problem in innovating good technology was that ideas of design features and functionality are based on documents (e.g., field notes) that often include omissions, biases and even distortions. These may, of course, easily lead to misunderstanding the social and psychological aspects of the use context. The notion of *bodystorming* refers to the simple idea that the design team does not speculate about use situations at their office, but goes out and innovates design on site. By “being there” (instead of remaining at the office), researchers can more easily focus their attention to relevant aspects of context that might not be available in documents.

Oulasvirta *et al.* (Paper I) adopted this idea from industrial design and developed it in four case studies. The method is as follows: before a bodystorming session, a preliminary observation and documentation is conducted. From the documents, interesting phenomena are selected and edited into *design questions* (e.g., “Go to a mall and innovate a system that helps elderly people to better remember product information.”) that present problems in the events, experiences, or practices of users. Participants then go to a representative environment and attempt to solve one design question at a time. Crucially, this attempt takes place in a context where the studied phenomena and people are *directly observable*. This is in contrast to traditional brainstorming conducted in office environment unrepresentative of the studied environment. In some cases, to encourage further re-enactment, participants in bodystorming are not just passive observers but are asked to act out the activities. Generated ideas are recorded on-site and later elaborated.

In four case studies, some parameters of bodystorming were explored to understand how they contribute to the quality of the design innovations. First, *similarity* of the bodystorming environment to the studied environment was considered an important factor, and identical or very similar locations preferred over staged ones. Bodystorming participants' ability to observe directly the environment and human interaction there was considered necessary. Second, *acting out* was observed to be frustrating and causing costly preparations. It was speculated, however, that it could be useful in the long run when participants get used to the method. Third, *inclusion of stories* from the preliminary observation data to accompany design questions was considered useful, although not necessary. Concrete stories can help to focus attention to aspects of context that could otherwise go unnoticed.

The method was subjected to evaluation, including an expert evaluation of how "socially plausible" the scenarios created in bodystorming were in comparison to those created in brainstorming. The conclusion was that the main benefit of bodystorming is that it creates highly memorable sessions and inspires researchers to criticize and develop their design ideas already on the site. Furthermore, bodystorming was argued to advance the analysis of kind of use situations that the members of the design team are most unfamiliar with (e.g., a senior center). Bodystorming should be seen as a way of playing with data in embodied ways, "being there", to enhance understanding of the problem domain. Ethnography is largely based on long-term stay within a culture, conversation analysis on tape recorded data distributed and analyzed in data sessions, and contextual design on the simultaneous use of several representation formats. In respect to these methods, the contribution of bodystorming lies in the utilization of collected observation data in a contextually situated design session. This provides a possibility for a larger group of people not familiar with the data to better understand the use situation and the resources available there. (See also Oulasvirta, 2004.)

3.2 Paper II: Observing Typical Behavior "in the Wild"

"[...] the first priority of studying cognition in the wild is descriptive, sort of a cognitive ethnography. Studying cognition in the wild is difficult, and the outcomes uncertain."

Hutchins (1995: p. 371)

Transforming the understanding gathered in user studies of mobility to a form that describes typical behavior "in the wild" in a concise and crystallized form useful for designers to think about the cognitive and other resources in mobility is crucial.

For this end, Tamminen, Oulasvirta *et al.* (Paper II) conducted observation studies to find *distinctive* (in comparison to static contexts), *general* (from the point of view of frequency), and *useful* (from the point of view of design) socio-psychological aspects of mobile contexts. It was argued that the characteristics would be useful to understand what restrictions and resources prevail in mobile use contexts.

To summarize, the results show that “mobility” is *socially structured* around *navigation*. Situational acts are embedded to planned ones in navigation—dropping by, ad hoc meetings, and other forms of sidestepping are socially motivated and require flexibility from the plans related to navigation. It was recognized that since mobile places are rarely private, personal spheres must be actively constructed and claimed by socially recognizable acts. Distinct temporal tensions (fluctuations of importance of time in relation to space) were identified—waiting for example—that pose radically different cognitive and social demands for behavior. It was observed that most problems in navigation were solved utilizing social contacts and only rarely by using schedules, maps or the like. Aspects of multitasking were also identified, most importantly how different stages in navigation (e.g., reaching the goal vs. calibrating speed) pose different cognitive and social restrictions for multitasking resources. Most importantly, some of these findings were related to the cognitive resources they demand. For example, space claiming is an act requiring visual attention to monitor nearby people. (See also Oulasvirta, 2004.)

The study demonstrates that ethnography is necessary for explicating and analyzing human resources in mobile contexts. In Paper II, some central social patterns of behavior that constitute the cognitive resources in mobile contexts were identified and explicated.

3.3 Paper III: Analyzing Resource Demands of Social Interaction

As argued above, cognitive resources play a central role in interaction in mobile contexts, and these resources are largely determined by the need for carrying out social tasks. At some point, however, *describing* social phenomena is not enough, but we need look at social phenomena at the micro-level to find how tasks are limited simultaneously and sequentially.

The *turntaking* approach by Sacks *et al.* (1979) emphasizes that social interaction has sequential structure that unfolds in time in the actions of the participating individuals. One of the basic ideas of *ethnomethodology* is that people actively construct their everyday life by subtly using different resources available to them in a given situation. Context is actively interpreted and

constructed, to be interpreted and renewed again in the subsequent actions of the participants. These actions are called *turns*, which often consist of speech, but may also include nonverbal acts: bodily orientations, gaze, and speech. The power of this approach is that social interaction becomes *operationalized* through concepts that are better recognizable, in principle, by context-adapting devices. Moreover, turntaking provides a conceptual framework for looking at how interactional acts emerge over time to compete of the human resources.

Oulasvirta and Kurvinen (Paper III) analyzed group invitations, a complex social practice, and evaluated how well turntaking could be operationalized into computational models in context-aware devices. The interest was not so much in dialogues or direct and explicit invitations such as invitations to events (e.g., parties or meetings). Instead, invitations were analyzed that are embedded in action and remain partly or completely implicit and yet recipients are able to recognize them as invitations and act accordingly.

Three cases illustrated how the participants actively transform their social contexts in turns. In all of the invitations, the *inviters* propose the *invitees* to meet at some time and place in the future. In the first case, the inviter attempts to invite friends to their favorite café by sending a simple SMS: “Kafka” (the name of the café). For the invitee, this marks a change in the inviter’s context that could be, but does not has to be, reacted upon. This invitation, consisting one nodal turn, while often failing to realize as a meeting, produces group awareness and coherence.

In the second case, a woman working at a children’s park invites parents to a sing-and-play. Here, the invitations are embedded in the small details of her interactions with the potential participants for the play. She greets some, nods or waves to others, but not all people in the park. While doing so, she makes sure that those who have participated in the game before will notice that she has arrived and the play is about to begin. Her selection of the walking route, greetings, and casual remarks are not just compliments but they also function as invitations to participate. Again, the invitations need not to be presented as direct verbal questions or requests. Even though sing-and-play is a scheduled event, it requires further specification of time and place, notifications to the potential participants, and gathering of those who eventually attend. That there is a sing-and-play every Thursday morning and that there is a poster on the wall constitute preconceptions that help to reason inviter’s intentions from her behavior. Furthermore, invitations are left implicit not only because the shared preconceptions make it possible, but also because it gives the invitees the option not to participate without having to give an excuse.

In the third case, journalists working in an open space office invite to lunch by loitering, with their coats on, in front of an elevator. The inviters know that at a given time, other journalists may have work in a phase not allowing for interruptions. They therefore have to balance between the convenience of having lunch together and the possible disturbance caused by the invitation. That is why the invitation has evolved into an embedded, yet easily recognizable, routine of hanging about at the exit with overcoats on before stepping out of the office. In contrast to the second case, there is no explicit prior agreement behind the invitation to lunch. Still, going for lunch, as a result of it being a daily routine, is easily recognized by the participants and offers similar resources for interpreting behavior. Whereas in the first and second example SMS messages and greetings were directed at specific individuals, the implicit invitation here does not have any recipients at all. Moreover, in contrast to the first two examples, the invitation was achieved in co-operation with others. A single person standing next to the exit does not make an invitation. The other journalists, still sitting at their desks, while recognizing that an invitation has been presented, may select themselves as being invited, even when the invitation did not specify any recipients.

Establishing just how social situations pose demands for cognitive resources is important to understand in analyzing mobile contexts, and the turntaking analysis, “the simplest systematics”, examined in this paper seems particularly suitable for this end.

3.4 Paper IV: Cognitive Resources in Temporal Tensions

Time per se has no causal power in HCI. Just as time is not the cause of rust, it is not the cause of delays, errors, mistakes or the like in interaction. Instead, the functional role of time emerges from the tension between our limitations in performing certain actions in a unit of time (e.g., walking speed has a practical maximum), the pressure to do the work in time, and the need to multitask. Because of these factors, people must continuously switch between tasks in coordinating their pace and keeping up with schedules.

Temporal tension, loosely speaking, refers to the availability of time for reaching a goal (Paper IV). It describes how adequate the pace of performance is for reaching the goal in the set timeframe. Even if “time” is a pervasive aspect of our understandings of the world, it can be also seen as a *resource* (or aspect of our shared cultural knowledge) to be potentially invoked as criteria for choosing future action or interpreting past ones. For example, “2 minutes” has different meanings for an ice-hockey team that has a penalty and to another team that now has a power-play situation—the orientation of the players to the future action is different.

Temporal tensions were identified from our mobility data by analyzing the situations where time has a peculiar relation to action and where our subjects themselves somehow orient towards it—thus making temporal tensions in their actions visible. The five temporal tensions were analyzed from the resource point of view and related to interaction (see Figure 1 in Paper IV). Each was related to the cognitive needs and resources.

Time has been an under-researched topic in human-computer interaction. To date, the concepts for describing the role of time in interaction have been scarce. Paper IV has presented a conceptual framework, inspired by ethnomethodology, for looking at time as a resource in human-computer interaction. The key idea is that external demands and intrinsic motivations create tensions that largely determine the resources available for various tasks carried out. The notion of temporal tensions is work driven rather than device driven, and it might prove fruitful for conceptualizing time in interaction.

4 DISCUSSION

In the following, the main contributions of the research is summarized and critically evaluated. To conclude the thesis, directions for future work are presented.

4.1 Contribution

A mobile person may need to keep in his mind route information, speak to his handy about a family affair, visit restaurant, order something, return to the main task, think about holiday, and keep all these tasks active until they are finished. Indeed, while mobile, we almost always have numerous unfinished, simultaneous, successive, and overlapping tasks. Keeping in mind all the known limitations in human cognition, one can only wonder how this is possible at all.

This thesis has presented a novel framework for looking at mobile interaction. It sets aside the normal cognitive approach in HCI where interaction is looked only from the point of view of carrying out one task to the end at a time, always aiming for maximum performance. Instead, it assumes that multiple tasks are carried out while mobile. Multitasking, according to the framework, yields costs for action and cognition: some tasks need to be slowed down, put on hold, or stopped. When the meta-level control for multitasking fails, errors, misconceptions, slowdowns, slips, and the like emerge. These costs, the usual and the extreme and rare, have been the main focus of this work: 1) what are they and how do they emerge, 2) how to analyze them, and, ultimately, 3) how to make them visible to designers?

To answer the first question, the present work has, through ethnographic description of mobile behavior, identified typical tasks that mobile people carry out while on the move. As stated by Hutchins, cognitive science “in the wild” starts by ethnographic observations of people, artefacts, and the environment. The five characteristics of mobile behavior, presented by Tamminen, Oulasvirta *et al.* (Paper II) does just this.

To answer the second question, the present work has examined ethnomethodology with the aim of finding the cognitive demands of turntaking people participate in everyday mobile behavior. The present work proposes the very first tentative links to bridge cognitive psychology with ethnomethodology. As argued in Paper IV, the analysis seems possible for phenomena that seem mentalistic from the outset, such as temporal tensions, as these are often triggered, upheld, controlled, and finished by external events, which makes them, in principle, perceivable for context-aware computers.

To answer the third question, the present work has proposed and critically evaluated the method of bodystorming for carrying out design sessions “in the wild”. As human resources, be they social or cognitive, are often poorly captured by rapidly crafted documents of user behavior, emphatic, embodied, and enacting approach to design can bring valuable information about use contexts and make the resources somewhat more visible than what they would be by conducting brainstorming sessions at the office.

As a whole, the present framework implicates a new look at mobile contexts—new for the human–computer interaction of context-aware technologies, but not for social and cognitive sciences, and their applications in the traditional HCI. To repeat, the basic assumptions of this approach are:

- Multiple tasks are carried out while mobile. These tasks relate to physical surroundings, other people, and computing devices.
- Resources for multitasking are limited,
- Tasks compete for the pool of resources. There must be a mechanism for deciding which task “wins” the limited resource at any time. Multitasking must be carefully planned in order to achieve the intended level of performance in each task.
- When the demands posed surpass the capacity, problems emerge that are reflected to all secondary tasks, including the tasks related to interaction.

Several factors were identified in Papers II and IV that modulate or intensify the need of a task for resources. Among some of the more interesting ones were:

- *Number of simultaneously performed tasks.* There are costs (attentional and memory-based) for frequent switched among tasks. The more tasks, the more resources are wasted for operating this meta-level control.
- *Modality overlap.* Competition for a modality or a cognitive module leads to postponement or dismissal of tasks from the cognitive system. Modality overlap at the level of perception, cognition, or response results in multitasking costs like these.

- *Task-difficulty*. Almost by definition, hard or difficult tasks are those that demand and tax our resources.
- *Task-novelty*. Novel tasks, in comparison to familiar, routinely performed tasks, are less likely to credit from automatization that saves central resources (e.g., working memory and attention). This result in greater demand for cognitive resources can only be modulated with practice.
- *Task composition*. The sequence of the actions that the tasks take, matters (cf. task hierarchy), as matters the distribution of actions between the context and the person. Perceiving turns reserves perceptual-attentional resources: attending to the place of expected turn and waiting and perceiving the turn. Interpreting the turn, in contrast, is more cognitive in nature, whereas responding to the turn requires co-ordination of action (in performing the turn), perceptual (in monitoring the action), and cognitive (in interpreting the own turn and the response of the other).

Taken together, an empirically and theoretically informed and justified conceptual framework is emerging from the present work. The main contribution of the present thesis is that it identified some of the most typical tasks carried out in mobility (Papers II, III, and IV), suggested several sources of resources that are available (i.e., Table 1), and proposed how the two are linked both theoretically (Papers III and IV) and in the practice of design (Paper I).

As shown in each of the particular papers, especially Papers II-IV, these resource limitations have wide implications for the design of interactive systems.

4.2 Evaluation

As most of the implications of the work have remained mere suggestions, it is hard to evaluate the approach by looking at the quality of the design innovations it has brought about. However, it is possible to look elsewhere in the literature to find examples of similar kind of thinking. Consider, for example, the following example by Ebling *et al.* (2002). Inspired by their analysis of mobility, they designed an improved version of their mobile file sharing system, Coda, where the operation of network was made transparent to the user, enabling them to make better estimations of when computing resources would be available. Support of planning and decision-making by making resources visible enabled novice users to perform at the level of experts in the tasks related to their system. Similar examples are not hard to found and three other examples of real interactive systems built by our team are given in Oulasvirta

and Tamminen (Paper IV). Thus, from the practical point of view of how well the approach supports design, it looks promising.

However, it is important to notice that the approach is limited in explanatory power. Laboratory experiments in psychology are situations where participants try to achieve their best in an artificial setting where they are evaluated and pressured by the leader of the experiment. Thus, they are inherently performance-oriented. Experimental cognitive psychology has throughout its history aimed at utilizing only objective measures of behavior, or measures that are free of subjective biases. Reaction time and accuracy and reliability of elicited behavioral reports have been the most widely used dependent variables. Consequently, cognitive psychology has been most successful in describing how well and within what preconditions people can achieve their goals. When performance breaks down and errors, omissions, distortions, slow-downs and other costs emerge, has also been the main focus in the present study.

Because of the approach, many important questions cannot be answered by the theoretical framework advocated here. For example, we cannot analyze exactly what motivates and drives people (motivations and needs) in mobility, how they feel about “being” mobile (emotions, phenomenology), how they learn and internalise the “scripts” of mobility (learning) and develop to become members of the mobile society (development) etc. At this moment, however, the cognitive question seems to be the easiest to tackle: what are the resources and restrictions people have for interaction in different mobile contexts. In summary, the cognitive approach in general, and the approach put forward in this thesis particular, has limited power in mobile human–computer interaction. Other “user psychological” approaches are needed to solve the other types of problems (Oulasvirta & Saariluoma, 2004).

At the moment, the framework may still look as positioned closer to folk psychology than the theoretical constructions of cognitive psychology. Looking at the preassumptions of the framework explicated above, it becomes clear that they do not contain very many *detailed* findings from cognitive psychology. For example, in the framework, we do not describe how long it takes to transfer information from short- to long-term memory, although this question was addressed already by Hermann Ebbinghaus (1885). Atkinson & Shiffrin (1968) suppose this time to be around 8 seconds. A time parameter like this could carry important implications on our ability to perform interactive tasks in a mobile context. This omission, however, is understandable from the point of view of how theories are developed and elaborated in cognitive sciences. Folk psychology and common sense are able to capture “large” effects of variables to another. Only with experimental methods can we elicit smaller

and smaller effects. In a field that has adopted an instrumental interest of science, such as human–computer interaction, the aim of research is not to reveal “truths” of nature, but to *inform* the design of ergonomic and enjoyable interactive systems. At the beginning stages of research, such as in the research of mobile contexts, the research is most likely to reveal the largest and most obvious effects, and as these may be familiar to the audience, findings may seem expected and trivial. However, the contribution of such research must lie in its attempt to explicate and describe in theoretical terms *typical* and *strong* phenomena. More work is needed to elaborate the framework and guide it closer to more current cognitive theories of mind.

The framework can also be evaluated from the point of view of “competing” theories. Here, the work on “distributed cognition” is most relevant. Distributed cognition (Hutchins, 1995) defines itself as “the emphasis on finding and describing 'knowledge structures' that are somewhere 'inside' the individual encourages us to overlook the fact that human cognition is always situated in a complex sociocultural world and cannot be unaffected by it” (p. 13). Moreover, “the environments of human thinking are not 'natural' environments. They are artificial through and through. Humans create their cognitive powers by creating the environments in which they exercise those powers” (p. 16).

As Distributed Cognition is associated most strongly with Computer-Supported Cooperative Work, or CSCW for short, it has been studying mainly work settings rather than free-time, leisure, entertainment, or everyday routines. Orientation towards work settings and knowledge work especially, has been natural for its attempt to model intelligence as distributed symbol processing systems. This approach, however, might not be as fruitful for everyday mobile interaction where interaction rarely fails because of misunderstanding a symbol, manipulating it in an unorthodox manner, or the like. Rather, routines in mobility fail more often because of cognitive demands of the situation reserve resources to the extent that slow-down, errors, or halts become inevitable.

It is important to state, however, that the framework presented here does not compete or try to replace the distributed cognition approach. By contrast, the idea is to take it closer to cognitive psychology of the individual. Distributed Cognition has been criticized as being *atheoretical* and separate from cognitive psychology. This is part because Hutchins explicitly attacks cognitive psychology in claiming that its results are not relevant “in the wild”, which of course is an exaggeration.

For cognitive systems that are being described at the “in the wild” level it is imperative to carry out extensive fieldwork and become familiar with the human practices. This entails observing them, making copious field notes, recording events and then transcribing and encoding these. An important part of this kind of ethnographic analysis is re-representing the raw data collected at different levels of abstraction and detail, focusing on the changes in representational state in the cognitive system. From this perspective, the approach presented here comes close to distributed cognition, only the focus of theoretical terms differ.

4.3 Directions for Future Work

Ultimately, the claims put forward by the approach should be tested empirically. If physical and social tasks compete for the same cognitive resources, different situations should have different implications for interaction. This simple claim could be tested if one could accurately measure how attention is distributed among different external sources (e.g., mobile device, physical environment, other people, navigation artefacts etc.) of stimuli in a mobile use situation and compare this to a laboratory situation where no such competition is present.

At the present, UERG is carrying out such experiment with Nokia and HUT where temporal tensions are manipulated by instruction (e.g., hurry vs. waiting vs. self-paced), social space by taking participants to places with different characteristics of present people (e.g., comparing buses, waiting rooms, cafes, and public outdoor places), and turntaking by looking at situations where participants are the ones to initiate the signal vs. perceive it vs. respond to it. Figure 5 illustrates the experiment. At this stage, 30 participants have participated to the two-hour experiment.

The results of this experiment will reveal concrete evidence on how different mobile contexts, through competing for our limited cognitive resources, carry over effects to interaction with mobile devices.

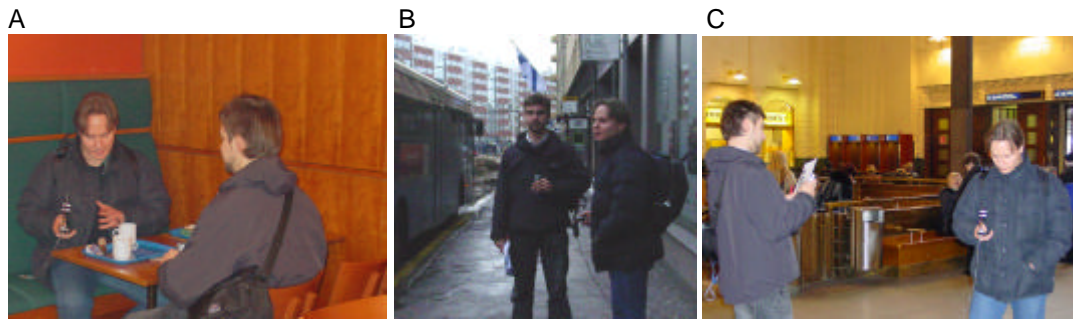


Figure 5. Quasi-experimentation “in the wild” with a mobile device. In order to test the idea of social factors of a situation competing for cognitive resources of the user, the experiment is carried out in various places in Helsinki, for example: A) café, B) on the streets, and C) train/metro stations. To record the focus of attention and user’s actions, the mobile device is augmented with two minicameras (one pointed at the eyes of the user and the second on the device itself), one is attached to the participant’s chest, and one overall recording is recorded by a minivideocamera held by the moderator (here, the man on the right side in figure A).

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