2006-004

Usability in Transportation –
Improving the Analysis of Cognitive Work Tasks

MIKAEL ERLANDSSON

UPPSALA UNIVERSITY
Department of Information Technology

UPPSALA
UNIVERSITET

UPPSALA UNIVERSITET

Usability in Transportation – Improving the Analysis of Cognitive Work Tasks

BY
MIKAEL ERLANDSSON

June 2006

DIVISION OF HUMAN-COMPUTER INTERACTION
DEPARTMENT OF INFORMATION TECHNOLOGY
UPPSALA UNIVERSITY
UPPSALA
SWEDEN

Dissertation for the degree of Licentiate of Philosophy in Computer Science with specialization in Human-Computer Interaction
at Uppsala University 2006

Usability in Transportation – Improving the Analysis of Cognitive Work Tasks

Mikael Erlandsson

Mikael.Erlandsson@it.uu.se

Division of Human-Computer Interaction
Department of Information Technology
Uppsala University
Box 337
SE-751 05 Uppsala
Sweden

http://www.it.uu.se/

ISSN 1404-5117
Printed by the Department of Information Technology,
Uppsala University, Sweden

Abstract

In most vehicle domains within the transportation sector, traffic is increasing and vehicles are becoming more technologically advanced. In addition to this, drivers are faced with conflicting goals, such as punctuality, maintaining safety, minimizing fuel consumption, ensuring passenger comfort, etc. When accidents occur, the drivers' actions and mishaps are often in focus, even though the work environment, the organization behind the drivers, and the educational level may provide equally important explanations for incidents and actions.

In this thesis, factors influencing operators' behaviour are acknowledged and attempts are made to understand how these factors affect vehicle operators in their daily work. Even though modern vehicles are equipped with new technology that supposedly aids drivers, studies of actual work typically reveal that these tools are not necessarily suited for their purpose.

In a larger perspective, it is necessary not only to improve this technology, but to redesign how vehicle drivers perform their work. In practice, also traditional processes for development of technology affect how the operators work, although then simply a side effect of technology being introduced. Based on a deep understanding of the operators' work, the long-term goal here is to instead design new ways of working that allows the operators to use their skills to do meaningful driving tasks supported by technology.

To acquire this understanding of how the operators work, a new method of information acquisition has been developed and tested within the rail and marine domains. These studies resulted with an understanding of what train and high-speed ferry operators are occupied with during their journeys, as well as insights into why they perform in certain manners and how they think and reason about these tasks.

List of papers

The thesis contains the following five papers, all with reprint permission from the publishers.

[I] Erlandsson, M. & Jansson, A. (in press). Collegial verbalisation – a case study on a new method on information acquisition, Accepted to Behaviour & Information Technology.

[II] Erlandsson, M. & Jansson, A. (manuscript). General domain properties in vehicle operation: A comparison between trains and high-speed ferries. Submitted to Transportation Research Part F: Traffic Psychology and Behaviour.

[III] Jansson, A., Olsson, E. & Erlandsson, M. (2006). Bridging the gap between analysis and design: Improving existing driver interfaces with tools from the framework of cognitive work analysis. Special issue of International Journal of Cognition Technology and Work (IJ-CTW).

[IV] Erlandsson, M. & Kavathatzopoulos, I. (2005). Autonomy method – acquiring skills for ethical analysis of computerisation in car driving. Proceeding of ETHICOMP 2005 - Looking back to the future, Linköping, Sweden. September.

[V] Erlandsson, M. & Jansson, A. (2004). Augmented reality as a navigation aid for the manoeuvring of High Speed Crafts. The 8th International Design Conference - Design 2004, Dubrovnik, Croatia, May 18-21.

Outline of thesis

This thesis consists of a summary followed by five papers. The summary is structured in the following way:

The **first chapter** gives a brief description of the studied work domains and discusses some problems related to these. A short description of my objectives towards addressing these issues is given.

The **second chapter** describes the theoretical grounds of my research, as well as the scope and limitations.

The **third chapter** (then) goes further into detail about the specific theories and methods used in my research.

Chapter four gives a more thorough description of the studied domains. First, a general description of socio-technical systems is given, followed by a section that addresses the issues of vehicle operation more specifically. The chapter ends with a section describing some special topics that are of particular interest for the research questions.

Chapter five describes how the research I performed is connected to the questions discussed in this thesis. Each paper is discussed specifically concerning how it relates to the other papers, as well as to my research questions.

Finally, **chapter six** sums up and discuss the major contributions of this thesis, and **chapter seven** highlights some interesting areas of future research.

The summary is then followed by five papers:

Paper I describes a new method for information acquisition that has been developed by our department called Collegial Verbalisation. This method is similar to retrospective verbalisation using video recordings, but here instead using close colleagues as subjects rather than the subject being video taped. This method has evolved and been refined at our department for some years, but this paper is the first to describe it in detail and address it specifically. I am the primary writer of this paper, undertaken with the collaboration of my co-author.

Paper II presents the results from case studies of trains and a high-speed ferry. In both studies, analyses of the drivers' work is based on the method described in Paper I. Based on the results of the two studies this paper compares three special topics related to vehicle control. The train study was performed by an earlier PhD-student. I performed the study onboard the high-speed ferry, the comparative analysis between the two studies, and guided by my co-author, I also wrote this paper.

Paper III takes a broader view than Paper I & II. The first part of this paper is based on work with the Collegial Verbalisation method to examine the driver environment of passenger trains. The resulting data is then used as input to the Cognitive Work Analysis (CWA) framework. The second and last part of the paper describes four design iterations of a User-Centred System Design cycle, with the goal of bridging the gap between analysis and design. My contribution to this paper is the part related to the analysis using the CWA-framework.

Paper IV describes a tool that can be used when involved in decision making tasks related to ethical factors. The idea is that, when making ethical decisions, one should strive for an autonomous perspective, and the tool gives guidance in this process. The paper presents a study where the tool is tested in a case involving car driver environments. I performed the study and wrote a substantial part of the paper.

Paper V deals with an experimental study of a new way of presenting information to high-speed ferry officers, called Augmented Reality. I performed the experiment and the analysis. I also wrote the paper with the help of my co-author.

Contents

1 Introduction 9
1.1 The problem 10
1.2 Research objectives 11

2 Research approach 12
2.1 Action research 12
2.2 Interdisciplinary research 14
2.3 Scope and limitations 15

3 Theoretical framework 16
3.1 Cognitive Work Analysis 16
3.2 Control theory 18
3.3 Method development 20

4 Operating a vehicle 21
4.1 Socio-technical systems 21
4.2 Vehicles and vessels 23
4.3 Issues related to understanding professional work 26
4.3.1 Automated actions 26
4.3.2 Tacit knowledge 26

5 Understanding vehicle operators’ work 28
5.1 Collegial verbalisation 28
5.2 Case studies 29
5.2.1 High-Speed ferries 29
5.2.2 Passenger trains 30
5.3 Autonomous method 31
5.4 Experimental studies 32

6 Reflection 35

7 Future work 37

Preface

Ever since I was a child, I have been good at understanding how other people perceive aspects in their environment. It is not that I consider this my calling in life, only that I have some skill in it. My mother once told me that, at the age of about ten, I often made long descriptions about events at school. E.g., how my teacher and my classmates had been discussing some matter, and that they didn't understand each other's point of view, but that I understood both parties very well and was frustrated about the miscommunication.

This little anecdote from my youth involves both the ability and the interest of understanding how other people perceive things. Both of these characteristics are necessary if such an understanding about others is desired. A respectful, attentive and perceptive approach together with continuous communication and the ability to restrict oneself from imposing ones own perspective to harshly is also valuable.

This short story is precisely what this thesis is about, although the following pages use a different terminology with words such as *autonomy, tacit knowledge* and *mental models,* as well as scientific methods and frameworks such as *collegial verbalisation* and *cognitive work analysis*. The context and purpose is of course different here, but the goal of understanding how others perceive phenomena, think and reason is all the same.

1 Introduction

Consider a 2000 metric ton ship with 1500 passengers travelling at the speed of 55 km/h in an archipelago. With the primary goal of safely reaching their next stop, the ship is controlled by a few bridge officers that lack the ability of making any fast changes to the ship's course or speed. In the archipelago, the traffic situation can change radically within a few minutes if other vehicles change their speed or if a new vehicle shows up from behind an island. Therefore, the officers continuously try to plan ahead to compensate for the ships' poor responsiveness.

Bridge officers' work typically consists of passive periods of monitoring intermixed with periods where more intensive action is needed, e.g. at berthing. In a low traffic scenario, the officers typically focus on monitoring tasks and planning as a way of remaining vigilant and reducing future burdens. But when navigating through crowded traffic, through archipelagos or while berthing, the officers are instead faced with vast amounts of dynamic data. This data is continuously integrated and interpreted by the officers, as a basis for decision making and potential actions.

During low visibility scenarios, the officers are forced to trust their computer system. A large modern bridge is a rather complex setup of electronics, including joysticks, buttons, knobs, and at least 10 monitors with their individual controls spread out over a large area. Different computer systems typically have its own unique software requiring many different forms of interaction by the officers. This non-uniform setup can be rather dangerous when an officer is put in a stressful situation and is forced to make quick decisions. Imagine a shaking and vibrating work environment full of noise and alarms, where the officers try to interact simultaneously with several computer systems, the bridge crew ground personnel, etc.

The complexity of the work environment in a modern ship leaves the officers with challenging tasks such as interacting with cognitively demanding technical systems, integrating information from many different sources, evaluating plans of actions in their head with little support, and choosing and executing actions based on the integrated information.

Descriptions of other vehicle domains would perhaps give a somewhat different picture, but many of the underlying issues of vehicle control are the same such as course or speed planning, monitoring the surroundings, etc. However, this thesis focuses on the studies of high-speed ferries and trains.

My motivation to work with vehicle driver environments is primarily that poorly designed work environments cause stress for the driver and sometimes accidents. Too often, accidents are blamed on the human operators rather than the poor work environment in which they are put. Vicente and Rasmussen (1992) argue that “slips (errors of execution) can be reduced through the application of ergonomic guidelines, mistakes (errors of intention) can only be prevented by considering the cognitive factors influencing operator behavior”. There are, of course, many factors affecting the situation, such as the social situation, organisational demands, the work environment including the vehicle itself and the surroundings, etc. In order to improve this situation it is necessary to understand how the drivers think and reason about their work.

1.1 The problem

It’s not easy to deal with the issues described in previous chapter, but much can be done. However, the complexity of the work performed by experienced vehicle operators is also transferred into difficulties studying that work. A long term goal of this research is to improve the work environments in such a way that the officers are supported in the decision making process. If this enhancement of the work environment is to be done successfully, it is fundamental to acquire an understanding of the officers’ work. How and why they work the way they do, how they think and reason about their work, and also how they want to work in the future, etc. This thesis is about acquiring this understanding.

Traditionally, many system developers let technical aspects rule their development process, and later let the users adapt to whatever comes out in the end. I agree with Alan Cooper’s (Cooper & Saffo, 1999) colourful description that the software engineers (i.e. the inmates) are in power (i.e. running the asylum), and that the only way to solve this problem (i.e. restore the sanity) is to let an interaction designer be completely responsible for any user-related design (both at interface level and below).

Another fast and easy way for system developers to find out more about users work could be to study any available normative description of it, such as instruction manuals, rule books, checklists, etc. Such documents are often, unambiguous, easy to relate to software development and therefore rather comprehensible to system developers. Unfortunately, they fail to adequately explain how the users actually work, but rather how management or former system developers want them to work. As long as one takes the information for what it is, studying this information should be better than having no information.

A more user centred approach would be to ask the users how they work. However, it is not enough with posing questions like: “How do you work?”, or “How do you perform the start-up procedure of your ship?”. Such broad questions typically result in very shallow descriptions of the users’ work. Such descriptions do not even have to be representative for how the work is actually carried out and can almost be acquired by just looking at the users work without asking them. For example, the users might recall things in the wrong order, forget important details, or simply believe that they do things in one way, while actually performing in another fashion and therefore provide a misleading story (van Someren, Barnard, & Sandberg, 1994). This is especially relevant for highly automated work tasks. Professional users even adopt rather automated processes in their work, such that they have difficulties expressing their actions in words (Polanyi, 1974).

1.2 Research objectives

This thesis discusses how one can acquire an understanding of how users think, one that improves upon the examples from the previous chapter. How can a more accurate, more reliable and detailed understanding be acquired? This form of understanding on how the skilled vehicle operators think about their work is necessary to have as input to system development design tasks.

I argue that this is an important aspect in order to avoid the significant problems present in the domain of vehicle operation. This thesis primarily focuses on the challenge of acquiring this understanding, with a later goal of designing more useful work environments.

2 Research approach

It is possible to approach these objectives from many different points of views, although from a usability perspective a holistic approach is necessary (Vicente, 1999), if any meaningful understanding of the vehicle operators' work is to be attained.

With a traditional positivistic research perspective, knowledge is typically generated by conducting small well-defined experiments, by logical deduction, or similar. This approach does not deal very well with the complexity of the real world. Qualitative aspects are difficult to understand, measure, or prove with such an approach. The scientifically well received method Fitts' Law (Fitts, 1954) is a good example of how a positivistic approach, to the task of measuring and improving usability, fails. Anyone using Fitts' Law to measure usability reduces the problem to a single variable which, even though it might be a relevant aspect, hardly tell us anything about the usability of the system as a whole (Beaudouin-Lafon, 2004). It is not enough with quantitative measures. I agree with Miles and Huberman (1994) that both numbers and words are needed if we are to understand the world.

As contrast to more positivistic approaches, Schön (1983) describes professional practice as having properties of uncertainty, instability, uniqueness, complexity and value conflict. In this world, a constructivist approach is more suited. There are many views of what constructivism is (Phillips, 1995), but they all share the common idea that learners construct, through reflection, a personal understanding of relevant structures of meaning derived from one's actions in the world (Fenwick, 2000). This epistemology allows us to study the complexity of professional work, here specifically, how vehicle operators think about their work.

As discussed in chapter 1.1 a shallow understanding of the users is inadequate. It is necessary to dig into the details of the studied work situation in order to understand the complexity of the specific work. This calls for a rather applied form of research, where it is not possible to abstract and generalise too much.

2.1 Action research

Therefore, as a result of studying usability within the domain of vehicle operation, I choose to base my research on the concept of action research. Action research allows us to study the complexity of real work in its specific context. Elliott (1991) defines action research as “the study of a social situation with a view of improving the quality of action within it”. Instead of independently validating theories and then applying them to practice, within action research, theories are validated through practice. More specifically, Kurt Lewin’s theory (Kemmis & McTaggert, 1990) describes the practice of action research as research "proceeding in a spiral of steps, each of which is composed of planning, action and the evaluation of the result of action". Kemmis and McTaggert (1990) describe action research using an iterative cycle (Figure 1).

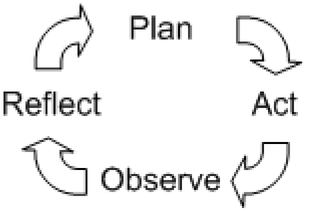

Figure 1: Kemmis’ iterative cycle of action research.

Scholl (2004) argues that “there is no standardized approach in the AR tradition, it rather comes in any flavors and formats such as educational AR, Action Learning, Action Science, Soft Systems Methodology, and others”. According to Scholl (2004) different AR approaches have in common that:

- “they actively involve practitioners and researchers in a project”
- “both groups jointly pose a problem, target one or more practical actions to address this problem, and study their outcomes”
- “the project is equally dedicated to the research side and to the action/outcome side”

At this general level, our research approach could be considered as action research, although some experimental parts of our work are not commonly associated with AR. However, Scholl (2004) face the same problem within the field of System Dynamics, and gives the following discussion of the subject:

> “On the continuum of research paradigms reaching from “purely” qualitative to “purely” quantitative methods, in most scholars’ perspective Action Research would find its place way towards the far end of the qualitative side, while hard quantitative methods such as computer experiments and computer simulation including System Dynamics (SD) would typically be situated on its far other side. For most observers, hence, there would not exist any odder couple than just those two with the widest possible margin on the continuum. A closer look, however, may suggest otherwise. Both methods deal with what Ackoff calls messy [1] and Checkland labels ill-defined problems [2], which

> are described as incompletely defined and rudimentarily understood problems due to their complexity in detail or in dynamics, or both. The study of social phenomena, for example, has encountered a myriad of problems of just this type. Messy problems of the dynamic kind have long resisted the ordinary scientific treatment of piecemeal reduction that Western science so successfully used over the past two centuries."

Similar to Scholl (2004), our approach to action research is partly concerned with experimental studies, but with a large focus on qualitative aspects of work. To further explain this approach, the following is a short overview of our research on high-speed ferry operators (Paper V).
Previous research at the department indicated that a new way of presenting information to the drivers was needed, and the concept of augmented reality was considered a possible solution to identified problems. The safety critical aspect of operating ferries unfortunately prevents new information systems from being tested within a real setting. A high speed craft (HSC) simulator had therefore been put together for this purpose. Earlier experiments in this simulator, using experienced navigators performing different simulated manoeuvring tasks, were made to compare the traditional way of presenting information to the driver and this new concept. My contribution was then to further iterate the results of this experiment, or *act* to use action research terminology, through *reflection* and *planning* into new experiments. As part of the same research project, observation and analysis of an HSC-bridge was performed (Paper II) using the method of collegial verbalization described in Paper I. This included video recordings, observations and semi-structured interviews during two case studies. The resulting data was later qualitatively analysed using Control theory (Paper II) and Cognitive Work Analysis (Paper III). Finally, it should be noted that project deadlines, financing, etc. has caused my own research contribution to be rather scattered, with respect to the more long-term iterations of action research.

2.2 Interdisciplinary research

Performing applied research in the area of vehicle operation, with all its complexity and challenges, also calls for an interdisciplinary approach. The young field of human computer interaction (HCI) is becoming large enough to contain its own theories and methods, but the traditional disciplines out of which HCI has grown still lends its theories and methods to the community. When HCI researchers apply these borrowed methods they tend to simplify or even misuse them, at least in the eyes of the original discipline. However, in order to get a broad understanding of the real work that is performed by experienced vehicle operators in their dynamic and complex world, it is necessary to be able to view the problem from many different directions and disciplines. In this case, my interdisciplinary perspective results in the use of a broad range of methods from several disciplines, such as anthropology, engineering, linguistics, experimental psychology, etc.

2.3 Scope and limitations

This interdisciplinary research has primarily been concerned with driver environments on high speed crafts and trains. However, the ideas and methods might work equally well for other types of vehicles, operators of complex socio-technical systems, or even any type of work involving expert users. Yet, no attempt has been made to test our methods outside the scope of high speed crafts and trains.

Within the field of HCI, my research is rather applied to its nature. So far, my work is restricted to the tasks performed prior to the design phase, i.e. primarily information acquisition and analysis. My work has included a few iterations of the information acquisition and analysis phases, but I have not yet been involved with any design iterations. Paper V, which is concerned with evaluating a new design concept using an experimental setting, could be considered both as an analysis of how operators' work is affected by a new information source and as evaluation of a this new way of displaying information to drivers.

3 Theoretical framework

The discussions in chapter 2 describe the grounds on which I base my research and with this position established, I now continue to describe the more specific theoretical focus of my research.

With background in the field of a computer science, my journey towards this thesis started off in the field of Human Computer Interaction. ACM SIGCHI Curriculum Development Group (1992, section 2.1) defines HCI as “a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them.” More specifically ISO 9241-11 (1998) defines usability as “The extent to which a product can be used by specific users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use”.

Before I go into detail about the theoretical focus, I want to point out that it is primarily my own process of learning the field of human computer interaction that motivated me to be involved with this research field. The performed research and resulting articles are largely products that can be attributed to my endeavour of learning the field. Later, this struggle will hopefully also aid me to direct future system development projects toward a more user-centred view.

3.1 Cognitive Work Analysis

Within the field of HCI, my research is based on previous research that originates from an ecological perspective. Partly my current focus is based on some general ideas found in the cognitive work analysis (CWA) framework (Rasmussen, Pejtersen & Goodstein, 1994; Rasmussen, 1986; Vicente, 1999). However, the more applied levels of the CWA-framework are not extensively used in this research. CWA focuses on complex socio-technical systems and therefore suits the study of vehicle operation quite well.

In relation to HCI, ISO 13407 (1999) describes a typical approach containing four fundamental activities that should be performed iteratively and starting early in the development cycle:

- understand and specify the context of use
- specify user and organisational requirements
- produce design solutions
- evaluate designs against requirements.

However, many researchers within the field of HCI agree with Vicente (1999) that:

> “This distinction between analysis, design, and evaluation is an abstraction and does not capture the actual practice of designers. If systems are to be built in an integrated fashion, then all three activities must all be intimately intertwined and mutually informing each other.”

I argue that, when studying socio-technical systems, humans and machines imply certain constraints that have to be accepted. One way of dealing with these constraints is the Cognitive Work Analysis framework (Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999), where ecological constraints are identified and considered before moving towards aspects that imply more cognitive constraints. There are many models and frameworks dealing with human actions in complex and dynamic systems, of which only some recognize the impact of the environment, e.g. theories of decision making (Klein, 1989), (Brehmer, 1992) and situation awareness (Endsley & Garland, 1999).

It is important to notice that CWA is neither a theory nor a method, it is instead a framework that describes how to identify behaviour shaping constraints in the environment and in what order these constraints should be taken into account. This is called a formative analysis in contrast to both descriptive and prescriptive methods for task analysis. The CWA framework is based on five levels of analysis, starting with an ecological perspective, and gradually moving towards a more cognitive approach (Figure 2).

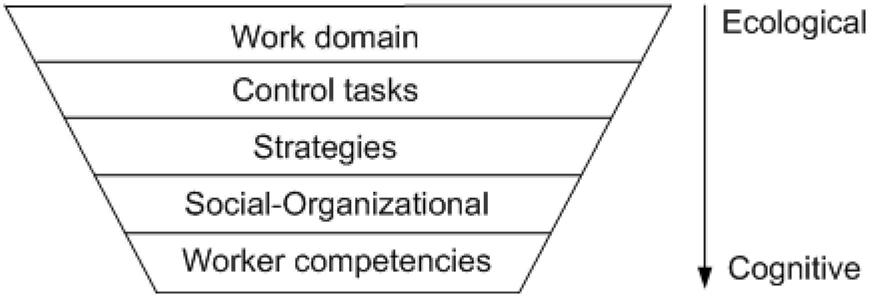

Figure 2: The five levels of analysis in the CWA-framework (Vicente, 1999).

Vicente (1999) uses the accident at the nuclear power plant Three Mile Island (TMI) and the operator's erroneous mental model that contributed to it, as an example of why environmental constraints should be studied in this order, e.g. taking work domain constraints into account before constraints of certain strategies are considered. According to Vicente, it would be misleading to base the design of a control room on operators' mental models since the mental model can be incorrect. The fact that the operators' mental models can be misleading does not mean that they should be ignored. On the contrary, the CWA-framework suggests detailed analysis of the operators work, e.g. using verbalisation techniques. Instead of relying on verbal protocols as fact, CWA tries to utilise such data to identify constraints of the environment. Furthermore, this structured approach can also result in the identification of operator misconceptions.

The term mental model is here used in a sense similar to the first description of it, made by Craik (1943):

> "if the organism [the human] carries a "small-scale model" of external reality and of its own possible actions within its head, it is able to try out various alternatives, conclude which is the best of them, react to future situations before they arise, utilize the knowledge of past events to react in a much fuller, safer, and more competent manner to the emergencies which face it."

I also agree with Rasmussen's argument that mental models are related to the knowledge level, referring to the highest level of the skills, rules & knowledge taxonomy (SRK) (Green, 1990). Furthermore, Brehmer (1987) adds that "information technology representations of processes are not only indirect and abstract, they are also (only) models created by designers for the purpose of handling a foreseeable range of decisions." I believe that this ecological approach is necessary, in order to achieve a design that, to a larger extent, accounts for events that where unanticipated by the system designers. The CWA-framework provides valuable information about intrinsic constraints of the studied work, which is of great importance when approaching design.

However, at some point, design ideas must deal with the specific requirements posed by the context of use. The second part of Paper III describes how User-Centred System Design (UCSD) and rapid prototyping is used to generate design solutions.

3.2 Control theory

Much like CWA, the concept of control theory has grown out of an engineering perspective, but both CWA and control theory are here used for the purpose of studying humans interacting with computers. We use control theory to describe, analyze and understand the work performed by primarily individual operators, however, groups and organizations can be studied using the same general concept. Our usage of control theory is based on Brehmer's (1991) idea that the mathematically grounded field of control theory can be used with a somewhat different goal within the field of HCI. According to Brehmer (1992), four basic criteria needs to be fulfilled if the operators should have a chance of successfully performing their tasks (Figure 3).

- There must be a goal.
- There must be a model of how the system behaves
- It must be possible to ascertain the state of the system
- It must be possible to affect the state of the system

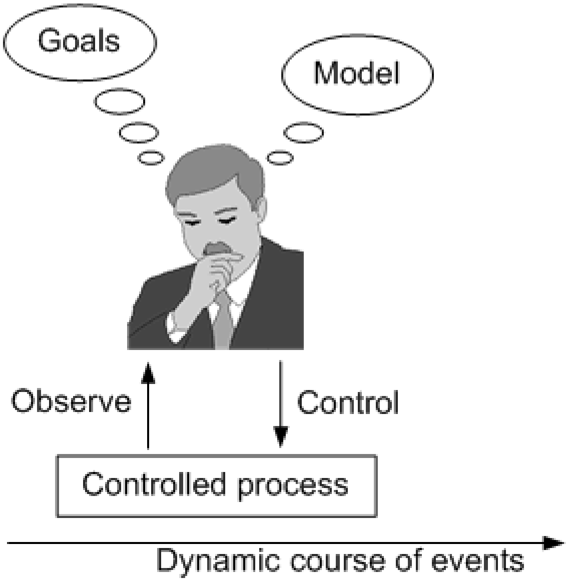

Figure 3: The four necessary conditions of control theory; the operator has a goal, a model of the system and some way of observing and controlling the process. If one of these conditions is not fulfilled, the operator will not be able to successfully operate the process.

This way of using control theory has been applied for many years by Andersson, Sandblad, Hellström, Frej, and Gideon (1997) in their work of designing new work tools for Swedish train dispatchers.

The control theory approach is not a comprehensive theory or model, but rather a framework for analysis which needs to be complemented on several aspects, such as the organizational level, competence, work ergonomics, education, etc. However, the tool provides a way of examining central aspects of operators of socio-technical systems, such as vehicles.

3.3 Method development

The young field of HCI, lacking a solid base of established theories and methods, makes it difficult to find theoretical grounds for research within the field. The previous two subchapters primarily describe theoretical frameworks for work analysis, rather than comprehensive theories about it. Even though the CWA-framework contains a set of methods for analysis, the actual methods applied in our research is mainly our own. A large part of my work has been to elaborate and develop methods for the specific problems at hand. In my research, a large effort has been put on formulating and developing a suitable method for information acquisition of vehicle operators' work (Paper I). Also, a method that aids autonomous decision making has been developed and tested in the area of road vehicle operation (Paper IV).

4 Operating a vehicle

Throughout this thesis, I have expressed that the studied domain of vehicle operation has certain properties that calls for specific ways of studying it. In this chapter, I discuss these properties in detail.

4.1 Socio-technical systems

Vicente (1999) describes socio-technical systems as consisting of an environment, organisation/management, workers and a technical system. He uses nuclear power plants and cooperative office work as typical examples of such systems. Vicente (1999) lists eleven characteristics of socio-technical systems, which I here present in an abbreviated form:

- Many different elements and forces create large problem spaces.
- Many people working together with a need of communication.
- Heterogeneous perspectives of the workers complicate but nuances decision making tasks.
- The work can be distributed spatially and over time.
- System output is affected both by current and previous actions, because of delays and slow propagation of actions.
- Potential danger for economics, natural ecology or public safety.
- A high degree of coupling between subsystems.
- Automation forces the operators to deal with situation where automation fails.
- Presented information might be erroneous, caused by sensor failure or other random errors, thereby creating an amount of uncertainty for the operator.
- Interacting with abstract information in user interfaces often demands more cognitive resources than when interacting with the ordinary natural environment.
- Disturbances, such as a fault in a process control plant that was not anticipated by the system designers, have to be dealt with by operators.

The list is presented here because I think that most of these characteristics apply to vehicle operators' work. Similar to Vicente's list, Dörner (1996) uses characteristics such as “complexity, intransparence, internal dynamics, and incomplete or incorrect understanding of the system” to describe properties of intricate situations where decision makers are forced to plan and act. Another characteristic that is closely related to the ones just listed, that I want to add is nonlinearity, e.g. when small changes to a system give little effect and somewhat larger changes can give dramatic effects. By being aware of the existence of such characteristics, it is possible to better understand the challenges and problems that workers are faced with. Furthermore, Perrow (1999) adds to this discussion that all risky systems should have more quality control and training, but where complexity and coupling lie, it will not be enough. Train dispatching (Figure 4) is a good example of a socio-technical system that is affected by all of the factors discussed above.

Figure 4: Swedish train dispatchers, busy integrating information and making decisions. Each dispatcher’s desk contains at least six monitors, three keyboards and several communications systems. Furthermore, all dispatchers share an entire wall covered with large monitors.

The challenging properties described above are closely related to the field of Naturalistic Decision Making (NDM), which came out of Klein’s field studies of fire-fighters, intensive-care units, etc (Klein, 1989). NDM argue that peoples’ decisions are made in a context, and that they are not the optimal solution, but rather a solution good enough for the problem at hand. In daily life, most decisions are efficiently made in a naturalistic manner, typically in situations with limited amount of time, inadequate background information, imprecise goals, etc. Decision making is one of the most fundamental and crucial tasks for a vehicle operator and I consider NDM to give a very realistic description of how decision making actually takes place in practice. Without an understanding of the field of NDM, it is easy to be deceived into believing that humans are logical and predictable creatures that always perform optimally.

Concerning the characteristic related to automation, Perrow (1999) gives a strong example of when automation fails. He refers to a New Zealand sightseeing flight where the autopilot route of the airplane had been changed without informing the pilot. Unfortunately, nobody onboard the plane noticed that this new route led straight into the Antarctic mountains until it was too late to take any evasive manoeuvres. Bainbridge (1987) describes that automation has a tendency to increase both stress and fatigue, since the operator is left to do the tasks that automation can not handle. This typically leaves the operator with long periods of inactivity combined with short periods of intense activity, which quite well explains how the flight accident just described could occur. An operator stuck in such a scenario is described by Endsley and Kiris (1995), as being out-of-the-loop. That is, automation is doing the job until the point where it fails and leaves the resulting abnormal situation to the vehicle operator, who then has to switch from an inactive state to the stressful task of acquiring an understanding of the abnormal situation in order to take necessary actions. Both the stressful state and the inactive state are problematic. When inactive there is a problem of vigilance. Bainbridge (1987) states that it is impossible even for a highly motivated human being to maintain effective visual attention towards a source of information on which very little happens, for more than about half an hour. If the operator is in a highly demanding situation, there is instead a problem when the demands on the mental workload get to high.

A recent study of a large number of train accidents (Kecklund, Ingre, Kecklund, Söderström, Åkerstedt, Lindberg, Jansson, Olsson, Sandblad & Almqvist, 2001) concludes that most of the examined accidents had been preceded by a deviation from normal operating circumstances, and that stress and fatigue was a contributing factor in roughly one third of the accidents.

Based on these issues with automation, Sarter, Woods and Billings (1997) argues that an automated system cannot know everything about its environment. Therefore, an operator has to supply it, monitor the outcome, etc. Thus, automation doesn’t reduce workload, but rather makes it unevenly redistributed (to e.g. the time critical parts of a flight). Jordan (1963) summaries this brilliantly, when stating that “we can never assign them [the machines] any responsibility for getting the task done; Responsibility can be assigned to man only”. As long as human operators bear ultimate responsibility for operational goals, they must be in command. To be in command effectively, operators need to be involved in, and informed about, ongoing activities and system states and behaviours (Billing, 1991).

4.2 Vehicles and vessels

In the specific profession of vehicle operation, the drivers are challenged with the complex and time critical task of controlling a moving vehicle (i.e a dynamic system) in real-time. It is often necessary to make instant decisions based on incomplete information, and these decisions are not necessarily expected, but rather an effect of the event driven property of the work.

Airplane pilots, ship officers, train operators and drivers of road vehicles all have to deal with this challenge in order to get from A to B, preferably without putting themselves, the passengers or the surrounding traffic at any unnecessary risk. This challenging task involves operators interacting with the outside world and the onboard driver environment.

The outside world sometimes poses difficult traffic situations or disturbing weather conditions (Figure 5). There are general weather conditions such as bright sunlight, fog, darkness or strong wind, but also more specific ones such as rough waves and currents at sea, slippery rail lines caused by leaves, etc. Traffic situations are generally resolved autonomously either by the involved drivers, by centralized vehicle dispatchers or any combination thereof. The rail and flight sectors traditionally use vehicle dispatchers, and as of late, the shipping industry has increasingly become centralized, especially when navigating to ports or through narrow passages.

Figure 5: Crowded traffic situation in Hong Kong.

The onboard driver environment poses a more technical challenge, where the interaction with joysticks, buttons, displays, etc., is used to control the vehicle (Figure 6). The operator needs to integrate information from many different sources of information in real time to stay updated with the current situation.

Figure 6: A modern centre console on a high-speed ferry bridge.

Larger vehicles suffer from feedback problems, e.g. the delay from an executed command until it has effect on the vehicle. Furthermore, corporations responsible for the vehicle operation can sometimes cause individual drivers to feel forced to perform unwanted operations. From analysis of the ship-navigation task, made by Carstensen, Nielsen and Schmidt (1997), a distinction between five categories of activities was made:

1. Monitoring the state of affairs.
2. Planning for future actions.
3. Deciding on navigation actions.
4. Distributing information, both within the watch arrangement and to external actors.
5. Monitoring other crew members' activities.

The challenging task of controlling a vehicle rarely leads to accidents but more often to incidents. Most investigations concerning deviations from normal procedures find several different causes for the mishap, often including some unfortunate action performed by the operator. In order for operators to avoid such situations, it is, among other things, necessary to have reasonable organisational demands such as a manageable timetable, but also to have a reasonable work environment where the operators can successfully affect the outcome of their job.

The complexity of modern work tasks in socio-technical systems does not allow the operators to modify their tools and tasks in the same way as before there were any mass-produced machines and computers. But the operators still have very much skill, work pride, experience and ideas of how to enhance and help evolve their workplace. Even if the operators are neither allowed nor able to reprogram their computer systems, they sometimes solve their issues anyway. For example, on some ships I have seen small plastic boxes covering certain buttons of the bridge console to prevent them from being pressed.

4.3 Issues related to understanding professional work

With respect to the overall goal of acquiring an understanding of how skilled vehicle operators think about their work, I have chosen here to go into detail about a few areas of special concern.

4.3.1 Automated actions

Skill is a factor of great importance in this thesis. Rasmussen's (1983) skills, rules & knowledge-taxonomy (SRK) describe the skilled level of work as automatic, not available to conscious thought or direct verbalisation. On the rule based level, behaviour is a conscious activity based on dictated or acquired rules, for situations that are rare but known to happen. The knowledge level is the highest and most demanding level, where direct rules can not be applied directly. Instead, some thinking and reasoning is necessary first.

Different from Rasmussen, Hammond's (1995) Cognitive Continuum Theory, derived from Brunswik, instead suggests that human cognition may oscillate between "intuition" (skill) and analysis (knowledge). The two ends of this continuum are exemplified by modern (knowledge) vs. prehistoric (skill) hunters. The modern hunter (a military general) makes conscious retraceable decisions according to some form of plan, while the prehistoric hunter reacts simultaneously to stimuli (visual, audial, etc.,) and makes non-retraceable instantaneous decisions.

4.3.2 Tacit knowledge

For example, Polanyi (1974) point out that when we acquire skill we also acquire a corresponding understanding that defies articulation. In other words, professional skills are typically tacit to some extent. Polanyi (1967) distinguishes between tacit and explicit knowledge. Tacit knowledge is described as being personal, thereby hard to formalize and communicate, and as being deeply rooted in action, commitment, and involvement in a specific context. Polanyi uses face recognition as an example of when "we know more than we can tell," i.e. humans are able to recognise a person's face, without being able to describe how it is done. This implies, among other things, that even if an operator really wanted to describe their how they think and reason about their work, the human mind sets limitations to this process. Nonaka (1994) divide tacit knowledge into a cognitive element related to mental models, and a technical element that covers concrete know-how, crafts and skills that apply to specific contexts. Explicit knowledge, on the other hand, “can be expressed in words and numbers, and easily communicated and shared in the form of hard data, scientific formulae, codified procedures, or universal principles” (Nonaka & Takeuchi, 1995), such as math formulas, technical specifications, computer software code, etc.

When discussing tacit knowledge with one of my colleagues at the department, I ones used the term silent knowledge as a synonym of tacit knowledge, after which he soon replied:

> “Silent knowledge? But it is not silent; it rather burst out if one is willing to see it.”

After some further discussions, I understood more clearly his point. There is so much information to find when studying skilled work, and even though it might not be explicitly presented orally, or as a set of well defined facts on a paper, the knowledge of skilled operators is very much speaking through the acts performed during their work.

5 Understanding vehicle operators' work

So far, I have presented my view of the work domain, a few problems, my research objectives addressing these problems, and my theoretical framework. The following chapter primarily accounts for the connections between the five papers in this thesis, as well as how they work together towards addressing the research objective.

5.1 Collegial verbalisation

The largest part of the work in this thesis is concerned with a new information acquisition method. This method was developed and tested at our department, for the purpose of better understanding how vehicle operators think about their work. This method, based on the concept of verbalisation, aims to give insights into tacit knowledge, mental models and automated actions of skilled operators. Paper I propose, explore and discuss this new method called collegial verbalisation. The method is especially well suited for the challenges posed by analysis of vehicle operation, but general enough to be used in any situation involving expert users. The method involves verbalization, as a way of getting closer to an understanding of the mental organization of vehicle operators' work tasks. There are many problems reported with verbalization techniques that one must be aware of, but the lack of substitutes still compels its usage. Nisbett and Wilson (1977) points out that subjects describe their own behaviour in a reconstructive and interpretative way, rather than by true introspection, and van Someren et al. (1994) states that an operator might give a perfectly good explanation of some action taken and might also be completely confident about truth of the verbalized information, when it in fact is incorrect.

Paper I describes a verbalization method that involves vehicle operators being video taped while manoeuvring their ship, followed by colleagues making verbal reports while watching this video data. The main advantages with this method, as compared to traditional verbalization techniques, are that it provides more exhaustive data since several operators can verbalize the same video data. Furthermore, since the subjects on tape are not part of the verbalisation, problems with the rationalisation of one's own behaviour are reduced. Within the field of vehicular operation, another valuable aspect is that the operators are relieved of the duty of driving, since the verbalisation is performed from video data. This method is still evolving, and needs further testing.

5.2 Case studies

Paper II describes how the collegial verbalisation-method was applied to driver environments of high-speed ferries, and Paper III describes a similar study involving passenger trains. The outcome of these studies is mainly of qualitative nature.

5.2.1 High-Speed ferries

The case study onboard a high-speed craft (HSC) was done with the goal of acquiring a better understanding of how HSC-operators think about their work, in order to later be able to design more useful work environments. Paper II, which mainly is concerned with the data acquisition and analysis phases, presents the results of a researchers' analysis of the outcome of the collegial verbalisation method. The data is structured and analysed using control theory (described above).

Figure 7: Four video images from cameras onboard a high speed ferry, shown during the verbalization phase of the collegial verbalisation study.

The study resulted in a detailed description of how HSC-operators generally work, especially how they think about their own work, with focus on aspects that relates to their information environment. This description, which is rather scattered and non-uniform, gives many insights into the complexity of HSC navigation and manoeuvring, but the step towards creating new bridge designs is still quite far off in the distance.

The control theory analysis resulted in descriptions of abstract goals, how they prioritize between different goals, how the goals were put into action by the officers in their daily work, and if they recognized any goal conflicts. The officers' mental models of the ship, in relation to the steering task were examined. The officers were planning ahead quite far, in order to deal with the slow propagation of steering commands. One officer argued that, with the radar set on 20 nautical mile scale with off-centre mode and a ship speed of one nautical mile in two minutes, he knows where the ship will be 40 minutes later. Another officer described that, in the archipelago, he used to think about the distance at which the ship would come to a complete stop, given the current speed. The question of how the officers actually deal with the long time horizon needed because of the slow effect of steering commands is very interesting, especially in relation to what the bridge provides in terms of possibilities of performing observation and control. In addition to this, some special questions were examined such as what subparts the operators consider a trip to consist of, and when the officers plan ahead, when they reflect on previous events or when they focus on present issues. The study identifies spatial separation made by the HSC-drivers, as well as three temporal perspectives of importance.

These distinctions, particularly the temporal, are related to the two control strategies proposed by Hoonhout and Zwaga (1993), management by exception and management by awareness. The former refers to when operators wait for an exception to happen, e.g. an alarm, before they take any action, while the latter is when operators continuously study the process, thereby being able to minimize exceptions by a continuous control of the process.

5.2.2 Passenger trains

Paper III describes a similar but more extensive study, using the collegial verbalisation method, but here to study train cabins. There are many similarities, but of course also differences between ship and train operation. However, studying both resulted in synergetic effects. One example is that operators' work is greatly affected by different time horizons. The collegial verbalisation method used here resulted in valuable information that later could be used in a work domain analysis. My contribution to this paper was primarily this work domain analysis, using the abstraction-decomposition space of the CWA-framework. Based on these results as well as results from recognition tests and interviews, it was concluded that the train drivers' work can be divided into three rather differentiated time intervals:

1. A long-range interval with an interaction between the train and a rather distant environment.
2. A short-term interval, with an interaction between the train-cab and the visible surroundings.
3. An immediate sense interval, with an interaction mainly in terms of braking and feed-back from the stopping train.

This paper goes one step further than Paper II, by applying the obtained results in a user-centred system design approach using domain experts (i.e. real users) in order to deal with the specific requirements posed by any actual system. The resulting design solution aided the three identified planning horizons, and clearly supported what Hoonhout and Zwaga (1993) refers to as management by awareness.

5.3 Autonomous method

This act of recognizing how other people think and reason involve observation, analysis and reflection. By trying to understand how others perceive the world, one's own representation becomes broader and more complex. This approach is contrasted by people who tend to keep a more narrow belief, avoiding or ignoring, any ideas except their own. Psychological theory (Kohlberg, 1985), (Piaget, 1932) differentiates between these two approaches, where the former is called autonomy and the latter heteronomy. Paper IV proposes the usage of an autonomous approach when making decisions concerning applied ethical matters. However, the general concept of autonomy is not at all limited to the ethics discipline, even though being of great value there. For example, an autonomous approach is also important in order to understand a computer user's needs, interests, problems, goals, etc. That is, to accept the challenge of trying to understand the complexity and the richness of details of the concerned environment or studied problem, challenge, or task.

The autonomous method described in Paper IV is a way of structuring and supporting decision making. This time consuming method stimulates the decision maker to strive to get an autonomous perspective. This is achieved by considering as many aspects of the problem as possible and also to consider how each involved person is affected by any possible decisions. This approach, which is as far from the naturalistic decision making described earlier, demands great resources, effort and will, but lays the foundation for a more thoroughly investigated and well considered decision as well as a form of documentation.

It is worth mentioning that when using the autonomous method, one should have the ambition to understand as much as possible, while keeping in mind that one will never attain a complete picture. Furthermore, the method does not provide any normative answer, but rather lays out the complexity of the situation for the decision makers so they can make informed decisions based on this information.

Paper IV describes a way of working that aids decision makers to acquire a higher level of autonomy. Decision makers need no experience into the theoretical discipline of ethical science. The goal is to aid decision makers in focusing on ethical aspects in areas such as software development or medicine. The Therac-25 accidents (Leveson & Turner, 1993) is a classic example of how terribly wrong things can turn out, especially in situations that can have direct impact on peoples lives, such as medical applications. The interaction with the Therac-25 was so poorly designed that the medical staff on several occasions thought they were giving their patients electron beam treatment, while the machine instead happened to be in the mode of delivering deadly doses of x-ray photons. The accidents of the Therac-25 radiation therapy machine, causing the death of several patients due to the lack feedback to the users, is a striking example of the ethical aspects in both medicine and software development.

A simple method involving a matrix, that structures the task of decision making, is described and exemplified. This was initially done to examine ethical aspects of the introduction of navigation systems into the driver environments of cars, but it later became clear that the autonomous-method can be valuable in all sorts of situations. Autonomous thinking as a concept is well suited for science, but general enough to be used anywhere, such as in one's profession or private life.

The autonomous method proved to be useful in the case study where navigation systems in cars were examined. Working with the matrix clearly aided the process of understanding how different people, organizations, etc., would be affected by different decisions. However, it is not the matrix itself that solves any problem. It rather provides the necessary support for decision makers to reason on their own. Any way of achieving such an aid would be useful. Furthermore, the tool needs to be tested further in settings that are more real, involving professional decision makers that are novices to the concept of autonomous thinking.

5.4 Experimental studies

The last contribution to this thesis (Paper V) is also related to the analysis of vehicle operators' work, but here in a more experimental fashion. Specifically, the paper describes an experiment where experienced high-speed ferry operators drive in a simulator.

Previous research at the department indicated that a new way of presenting information to the drivers was needed, and the concept of augmented reality was considered a possible solution to identified problems (Olsson, Seipel & Jansson, 2002). Several experiments in a high speed craft simulator were performed to compare traditional way of presenting information to the driver with this new concept. Ever since the radar was introduced onboard ships, it has been a valuable source of information, especially during low visibility. One problem is that the officers have to trust the radar image completely in such situations. Slowly GPS and electronic charts are becoming more common and sometimes integrated with the radar. The way that the radar technique works, unfortunately, has its share of drawbacks, e.g. waves and smaller boats can sometimes be difficult to distinguish from each other on radar. Waves (sea clutter) can be removed automatically, which also might remove small boats. Sometimes the radar image is difficult to interpret, because of radar shadows or false echoes. These issues have resulted in many accidents over the years, such as the one with the high-speed ferry MS Sleipner (Statens forvaltningstjeneste, Informasjonsforvaltning, 2000).

In the study of Paper V, we used a graphical high speed craft simulator to perform experimental studies with experienced HSC-navigators. A number of variables were measured in an experimental psychology fashion. The goal was to examine a new way of presenting information to the drivers; a technique called augmented reality. In the simulator, augmented reality is formed by presenting scene-linked information on a heads-up display (a transparent screen, generally located above the instrument panel of a vehicle, on which graphical information can be presented.) Scene-linked information is presented on a heads-up display in such a manner that it is perceived as being positioned in reality (Foyle, McCann & Shelden, 1995). The goal of using augmented reality here is to support the navigators' information retrieval task. This is done by allowing the user to keep direct visual supervision of the out-the-window scene using augmented reality. The information traditionally presented using ordinary instrumentation is thereby accessible without having to look down, e.g. to look at the radar screen. The safety critical aspect of high-speed ferry operation unfortunately prevents new information systems from being tested within a real setting; otherwise, this would be preferred as a complement.

The results of these experiments illustrated that there are many complex issues left to comprehend, but that the concept itself is promising. Similar ideas are now being studied by researchers with a closer relation to the maritime environment (e.g. Bjorneseth, 2003). We examined a simplified and simulated version of the complex and qualitative task of navigation, but the results of the study were mainly of the quantitative kind. The results provided valuable information, but were too limited with respect to the system as a whole. Nevertheless, while performing the experiments and watching the operators interact with the simulator, spontaneously comment and reflect on the pros and cons, many valuable qualitative results were received as well.

6 Reflection

Throughout this thesis I have pointed out that vehicle operators are faced with a challenging task and that my goal is to understand how the operators think about their work. The more I learned about *how* to form an understanding of *how* the operators think about their work, the more I realised that this also was a challenging task. The open minded, listening, reflective, analytic and self-critical approach necessary to successfully understand how vehicle operators think about their work is closely related to the autonomous perspective described in Paper IV. However, it is worth questioning, is it at all possible to understand *how* the operators think about their work? I argue that it should be possible, at least to some extent, but that issues such as verbalisations of implicit knowledge, communication or miscommunication, lack of common ground (Clark, 1996), etc. affect the result.

From an NDM point of view, operators performing decision making typically have models (mental or explicit) of how things around them function. Compare, for example, these two descriptions of how a ship joystick works:

1. Turning this joystick left turns the ship to the left.
2. Turning this joystick, sends an electrical signal to a computer, that calculates the adjustments to each individual propeller, which then affects two separate hydraulic systems that turns the propellers appropriately.

It is of course impossible to know if the differences between these two statements reflect differences in their respective mental models, or if it is a result of different verbalisation abilities. However, it still exemplifies that operators' mental models can be on completely different levels of detail and more or less erroneous. So, if it is not possible to understand exactly how the operators think and reason, what then is the point? It might not be necessary to know the 'truth' about these things. Even a more general understanding of how operators think and reason regarding relevant details of their work is a valuable source of information. It is also a good start when aiming to redesign their work environment and thereby also redesigning the work that will be performed in this new environment.

In some sense, this leads us to a never-ending loop, where modifications to the work environment affect the work performed in it, which makes the knowledge about their work obsolete. This procedure creates the need to test and evaluate the modified work environment, before it is possible to find out how the operators think and reason about their new work, what mental models they form, etc. This need of an endless looping is one reason why the design process should be iterative.

To sum up, trying to acquire knowledge of how the operators think can be complicated by “erroneous” mental models, communication without common ground, problems related to verbalisation of tacit knowledge, etc. Despite these problems they are still a primary source of information, because it is the operators themselves that are the experts, they are also the reason and target of any work to improve usability. Verbalisation methods are traditionally used for this purpose, and this often results in essential data. Papers I, II, and III pointed to some problems with traditional verbalisation methods and also explored a new method that partially solved these problems. This method was primarily developed with the goal of studying vehicle operators. Applying this method on case studies provided valuable but scattered knowledge regarding how vehicle operators think about their work, but it is still unclear how to proceed from there. How can this method and its results be used in an iterative systems development process?

Now at the end of this thesis, to sum up a few years of research, it would be in place to answer the following question:

How do vehicle operators think and reason about their work?

Well, one answer is given by the high-speed ferry operators themselves, exemplified in this fragment of a verbal protocol from an interview with an HSC-navigator:

> “You want to see the buoys physically, but you also want to have them on the radar. To see that they are where they should be, by double checking as much as possible. One cannot trust the computers 100 percent, but in thick fog there is nothing else to do.“

Such verbal protocols contain insight into the operators’ ideas, concepts, rules of thumb, etc. of their work, by which they think and reason. It is these mental models that affect the operators’ work and they are valuable to understand when designing new work support systems.

7 Future work

So far, the purpose of my thesis has been to understand the vehicle operators' work with the intention of later being able to design useful work environments. This raises the important question of how the accumulated knowledge can be translated into design. An attempt to address this is made in the second part of Paper III, although much more research can of course be done. This paper describes how a design solution is formed based on a formative, top-down perspective, and a bottom-up perspective, where implicit decisions are reached by user representatives. Of course, other factors such as previous experience and general knowledge about the concerned domain, basic design guidelines and strategies, etc. also affect the resulting design ideas.

As has already been discussed in this thesis, user involvement in the information acquisition and analysis phases is important. In the broader context of system development, a user centred system design approach should cover all necessary phases of a project, iteratively. It would be interesting to evaluate the usage of the collegial verbalisation method, throughout such an iterative system development project.

Acknowledgements

Special thanks go to my supervisors, co-authors and colleagues at the department for all their support and many interesting discussions. Thanks to the project members of my research projects, and all the high-speed ferry operators and train operators that participated in experiments, verbalisations and field studies. I am, of course, also grateful for all the financial support necessary during this thesis work. Thanks to everyone reading and commenting on this text, especially the proof-reader. Finally, I thank my family and friends for their encouragement. Even though I decided not to mention any names, I still hope that I did not forget anyone.

References

ACM Special Interest Group on Computer-Human Interaction (SIGCHI) Curriculum Development Group. Technical Report, ACM, New York.

Andersson, A. W., Sandblad, B., Hellström, P., Frej, I., Gideon, A. (1997). A systems analysis approach to modelling train traffic control. Proceedings of WCRR ’97, Florence.

Bainbridge, L. (1987). Ironies of automation. In J. Rasmussen, K. Duncan, and J. Leplat, editors, New technology and human error, chapter 24, pages 271-283. John Wiley and Sons Ltd.

Beaudouin-Lafon, M. (2004). Designing Interaction, not Interfaces. Proceedings of Advanced Visual Interfaces (AVI’04, Gallipoli, Italy). ACM Press, New York, pp. 15-22.

Billing, C.E. (1991). Human-cenered aircraft automation: A concept and guidelines (NASA Technical Memorandum 103885). Moffett Field, CA: NASA-Ames Research Center.

Bjorneseth, O. (2003). HOTS (highway on the sea), a new approach to low-visibility navigation, MARSIM’03, Proceeding of International Conference on Marine Simulation and Ship Manoeuvrability, Kanazava Japan.

Brehmer, B. (1987). Development of mental models for decision in technological systems. In New Technology and Human Error, Eds: Rasmussen, Duncan, and Leplat. John Wiley and Sons, New York.

Brehmer, B. (1991). Styrning av system: Kognitionspsykologiska aspekter på modernt arbete. Människan i arbetslivet. Stockholm: Allmänna Förlaget.

Brehmer, B. (1992). Dynamic decision making: Human control of complex systems. Acta Psychologica 81, 211-241.

Carstensen, P. H., Nielsen, M. & Schmidt, K. (1997). Is it a bug, or is it a feature? Taking the social organization of work into account in human-machine systems design: Proceedings of the Allocation of Functions Conference (ALLFN'97), Revisiting the Allocation of Functions, Galway, Ireland, IEA Press, 1997, pp. 57-71.

Clark, H.H. (1996). Using Language. Cambridge University Press.

Cooper, A. & Saffo, P. (1999). The inmates are running the asylum: Why high tech products drive us crazy and how to restore the sanity. Sams: Carmel, IN.

Craik, K.J.W. (1943). The nature of explanation. New York: The Cambridge University Press.

Dörner, D. (1996). The logic of failure: Recognizing and avoiding error in complex situations. NY: Perseus Books Group.

Elliott, J. (1991). Action research for educational change. Milton Keynes: Open University.

Endsley, M.R. & Garland, D.J. (eds) (1999). Situation awareness analysis and measurement. Lawrence Erlbaum, Mahwah, NJ.

Endsley, M.R. & Kiris, E.O. (1995). The out-of-the-loop performance problem and level of control in automation. Human Factors 37 (2). 381-394.

Fenwick, T. (2000). Expanding conceptions of experiential learning: A review of the five contemporary perspectives on cognition. Adult Education Quarterly, 50 (4), 243-272.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47, 381-391.

Foyle, D. C., McCann, R. S. & Shelden, S. G. (1995). Attentional issues with superimposed symbology: Formats for scene-linked displays. Proceedings of the Eighth International Symposium on Aviation Psychology. Columbus Ohio State University.

Green, T. (1990). Limited theories as a framework for human-computer interaction. In Mental models and human-computer interaction I, ed. D. Ackermann and M. Tauber, 3–40. Amsterdam: North-Holland.

Hammond, K. R. (1995). Naturalistic decision making from a Brunswikian viewpoint: its past, present, future. In Klein, G. A. Orasanu, J. Calderwood, R. Zsambok, C. E. Decision making in action: models and methods. New Jersey: Ablex publishing.

Hoonhout, H.C.M. & Zwaga, H.J.G. (1993). Operator behaviour and supervisory control systems in the process industry. In Salvendy, G. & Smith, M.J., (Eds.). Advances in Human Factors/Ergonomics, 19A. Human-Computer Interaction: Application and Case Studies. Proceedings of the Fifth International Conference on Human-Computer Interaction, (HCI International '93), Orlando, Florida, August 8-13, 1993 Volume 1. p. 109-114.

ISO 9241-11. (1998). Ergonomic requirements for office work with visual display terminals (VDTs): Guidance on usability specifications and measures.

ISO 13407. (1999). Human-centred design process for interactive systems.

Jordan, N. (1963). Allocation of functions between man and machine in automated systems. Journal of Applied Psycology, 47 (3), 161-165.

Kemmis, S. & McTaggert, R. (1990). The action research planner. Geelong: Deakin University Press

Kecklund, L., Ingre, M., Kecklund, G., Söderström, M., Åkerstedt, T., Lindberg, E., Jansson, A., Olsson, E., Sandblad, B. & Almqvist, P. (2001). The TRAIN - project: Railway safety and the train driver information environment and work situation - A summary of the main results. Signalling Safety 2001, London, UK.

Klein, G.A. (1989). Recognition-primed decisions. In W.B.Rouse (Ed.), Advances in Man-Machine System Research 5, 47-92. Greenwich, CT: JAI Press.

Kohlberg, L. (1985). The just community: Approach to moral education in theory and practice. In M. Berkowitz & F. Oser (Eds.), Moral education: Theory and application. (pp.27-87). Hillsdale, NJ: Lawrence Erlbaum Associates Inc.

Leveson, N. & Turner, C. (1993). An investigation of the Therac-25 Accidents. IEEE Computer 25 (7), 18-41.

Miles, M.B. & Huberman, A.M. (1994). Qualitative data analysis. Thousand Oaks: Sage.

Nisbett, R.E. & Wilson, T.D. (1977). Telling more than we can know: verbal reports on mental processes. Psychological Review 84, 231-259.

Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. Organization Science 5, no. 1: 14-37.

Nonaka, I. & Takeuchi, H. (1995). The knowledge-creating company. New York: Oxford University Press, Inc.

Olsson, E., Seipel, S. & Jansson, A. (2002). Safer navigation at sea using augmented reality. Proceedings of HCI’02, People and Computers, Vol. 2, Springer Verlag, London, UK, 154-157.

Perrow, C. (1999). Normal accidents: Living with high risk technologies. (2nd ed.). Princeton, NJ: Princeton University Press.
Philips, D.C. (1995). The good, the bad, and the ugly: The many faces of constructivism. Educational Researcher, 24 (7): 5-12.
Piaget, J. (1932). The moral judgement of the child. London: Routledge & Kegan Paul (pp.1-103).
Polanyi, M. (1974). Personal knowledge: Towards a post-critical philosophy. Chicago, University of Chicago Press.
Polanyi, M. (1967). The tacit dimension. New York: Anchor Books.
Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. IEEE Transactions on Systems, Man, and Cybernetics, SMC-13, 257-266.
Rasmussen, J. (1986). Information processing and human-machine interaction: An Approach to Cognitive Engineering. New York: North-Holland.
Rasmussen, J., Pejtersen, A.M. & Goodstein, L.P. (1994). Cognitive systems engineering. Wiley, New York, NY.
Sarter, N.B., Woods, D.D. & Billings, C.E. (1997). Automation surprises. In G. Salvendy (Ed.), Handbook of Human Factors and Ergonomics (2nd edition) (pp. 1926-1943). New York, NY: Wiley.
Schön, D. A. (1983). The reflective practitioner. New York: Basic Books.
Scholl H.J. (2004). Action Research and System Dynamics: Can They Benefit from Each Other?, Proceedings of the 37th Hawaii International Conference on System Sciences.
Statens forvaltningstjeneste, Informasjonsforvaltning. (2000). Hurtigbåten MS Sleipners forlis 26 november 1999. Summary from: Rapport fra undersøkelseskommisjonen. Justis- og politidepartementet 8. november 2000, NOU 2000: 31, Justis- og politidepartementet, Oslo Norway.
van Someren, M.W., Barnard, Y.F. & Sandberg, J.A.C. (1994). The think aloud method: A practical guide to modeling cognitive process. London: Academic Press.
Vicente, K.J. (1999). Cognitive work analysis: Toward safe, productive, and healthy computer-based work. Mahwah, NJ: Lawrence Erbaum Associates.
Vicente, K. J. & Rasmussen, J. (1992). Ecological interface design: Theoretical foundations. IEEE Transactions on Systems, Man and Cybernetics, 22, 589-606.

Recent licentiate theses from the Department of Information Technology

2005-001 Jesper Wilhelmsson: *Efficient Memory Management for Message-Passing Concurrency - part I: Single-threaded execution*

2005-002 Håkan Zeffer: *Hardware-Software Tradeoffs in Shared-Memory Implementations*

2005-003 Magnus Ågren: *High-Level Modelling and Local Search*

2005-004 Oskar Wibling: *Ad Hoc Routing Protocol Validation*

2005-005 Peter Nauclér: *Modeling and Control of Vibration in Mechanical Structures*

2005-006 Erik Bängtsson: *Robust Preconditioned Iterative Solution Methods for Large-Scale Nonsymmetric Problems*

2005-007 Mei Hong: *On Two Methods for Identifying Dynamic Errors-in-Variables Systems*

2005-008 Niklas Johansson: *Usable IT Systems for Mobile Work*

2005-009 Magnus Evestedt: *Parameter and State Estimation using Audio and Video Signals*

2005-010 Paul Sjöberg: *Numerical Solution of the Fokker-Planck Approximation of the Chemical Master Equation*

2005-011 Björn Holmberg: *Towards Markerless Analysis of Human Motion*

2006-001 Linda Brus: *Recursive Black-box Identification of Nonlinear State-space ODE Models*

2006-002 Anders Hessel: *Model-Based Test Case Selection and Generation for Real-Time Systems*

2006-003 Therese Berg: *Regular Inference for Reactive Systems*

2006-004 Mikael Erlandsson: *Usability in Transportation - Improving the Analysis of Cognitive Work Tasks*

UPPSALA UNIVERSITET

Department of Information Technology, Uppsala University, Sweden