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What's in your mind?

Collegial Verbalisation - An ecological approach to knowledge elicitation

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Abstract
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Knowledge elicitation of the work of professional operators, using traditional methods such as concurrent or retrospective verbalization is problematic. Concurrent verbalization distracts the operators from their primary task, and the operators have difficulties in verbalizing about their automated work tasks. Retrospective verbalization on the other hand, suffers from rationalization problems. 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. To overcome some of these problems, this thesis presents a new complementary verbalization method called Collegial Verbalization (CV).

The CV-method utilizes the shared knowledge among work colleagues to improve the quality of the resulting information. The method consists roughly of the following steps; (1) Video tape subjects while they are working. (2) Play back interesting events to the subject's colleagues individually and let them verbalize on the subject's actions. (3) Compare the colleagues' verbal reports to each other to find similarities, differences, etc. Throughout my research I have formulated, defined and assessed the new method in detail. The method has been applied to study train drivers, high-speed ferry operators, train traffic dispatchers and the medical staff at intensive care units.

Comparative studies have shown; (1) that CV-protocols can be used as an independent source of data, (2) that colleagues produce reports with similar characteristics of retrospective verbal reports, (3) that the CV-method can produce more information than retrospective verbalization, because of the advantage of using multiple narrators. When the intention is to gather data as input to design, rather than establishing the original thought processes form the time of the studied events, the CV-method can also produce more reliable information than retrospective verbalization, because of the advantage of using multiple narrators.

Based on these results, I have concluded that the CV-method has a clear advantage as a complementary information acquisition method, when studying the work of professional operators. The thesis ends with a discussion about several additional possible applications for the CV-method, such as applied team learning or psychological research in the field of decision making.

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"It is frightening to believe that one has no more certain knowledge of the working of one's own mind than would an outsider with intimate knowledge of one's history and of the stimuli present at the time the cognitive process occurred"

Nisbett and Wilson - 1977

Preface

Ever since childhood, I have been intrigued in how other people perceive different aspects of their environment. My mother once told me that, at the age of about 10 years, I often gave long descriptions about events taking place in 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).

It is not that I consider this my calling in life, but rather just a small anecdote from my youth. However, for some reason, either by chance, predisposition, or the effect of the social environment, 25 years later I happen to work with questions related to the understanding of how other people perceive things. Such work requires both the ability and the interest of understanding how people experience the world, as well as a respectful, attentive, perceptive and analytical approach and the ability to refrain from imposing one's own values and beliefs.

The reason for this short reflection from my youth is that the primary goal of this thesis is to understand what's "*in the mind*" of others. Even though the purpose, context and language are different in this thesis, the goal of understanding how others perceive phenomena remains the same. Rather than making sense of one's schoolmates, the purpose here is to understand the work of professional operators in order to be able to improve their work tools/tasks. The context is, for example, a ship bridge rather than a schoolyard and the language involves terminology such as *tacit knowledge, mental models, verbal protocols* and *cognitive work analysis*.

List of papers

This thesis contains the following seven papers, all with reprint permission from the publishers. The papers are numbered based on the chronological order in which they were written. All papers, except paper I, have been peer-reviewed, either as full papers (II-VI) or as long abstracts (VII).

[I]   Erlandsson, M. & Jansson, A. (2004). Augmented reality as a navigation aid for the manoeuvring of high-speed crafts. **Proceeding of Design 2004, the 8th International Design Conference, Dubrovnik, Croatia, May 18-21**.

[II]   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, 8(1), pp.41-49.**

[III]   Erlandsson, M. & Jansson, A. (2007). Collegial verbalisation – A case study on a new method on information acquisition, **Behaviour & Information Technology, 26(6), pp. 535-543.**

[IV]   Erlandsson, M. & Jansson, A. (2013). Verbal reports and domain-specific knowledge: A comparison between collegial and retrospective verbalisation. **International Journal of Cognition, Technology and Work, 15(3), pp. 239-254.**

[V]   Jansson, A. & Erlandsson, M. (Accepted with major revision). Collegial verbalisation: The value of verbal reports from colleagues as subjects. **Theoretical Issues in Ergonomics Science.**

[VI]   Jansson, A., Erlandsson, M. Fröjd, C., & Arvidsson, M. (2013) Collegial collaboration for safety: Assessing situation awareness by exploring cognitive strategies. **Presented at Interact 2013 Conference, Human Work Interaction Design (HWID) workshop**.

[VII]   Jansson, A. & Erlandsson, M. (2013) Recognizing complexity – A prerequisite for skilled intuitive judgments and dynamic decisions. **Presented at SPUDM24 Conference, August 18-22 at IESE Business School, Barcelona, Spain.**

Reading instructions

Chapter 1 presents an introduction to three aspects that are highly relevant to my research: shared knowledge, challenging work contexts and work analysis. These three aspects together constitute the foundation of my work, and I will return to discuss these throughout the thesis. The chapter concludes with a presentation of the research questions that have driven my PhD work.

Chapter 2 describes a few aspects that have especially motivated me to study humans at work in the first place. That is, to provide a more safe and healthy work situation for the practitioners. There is a huge potential for improvements here. Analysing the work tasks might reveal that small simple adjustments to the work tasks might have positive effects on safety, health and productivity.

Chapter 3 strives to position my scientific approach to research by comparing it with other approaches commonly used within human-computer interaction (HCI). I describe several research approaches that would be relevant for my own research. These approaches include ethnography, simulation-based approaches and controlled method approaches. They explain similarities to my own research, or the reason why I have chosen another path.

Chapter 4 begins with defining my epistemological view. Then I proceed to restrict my own theoretical approach by describing how it is grounded in ecological psychology. To understand my own ecological research perspective a short historic background is given as to how ecological psychology influenced certain researchers within the field of HCI, specifically Jens Rasmussen's work that led to the Cognitive Work Analysis framework.

Chapter 5 focuses on different methods of analysis relevant for studying professionals at work. Based on the theoretical foundation in Chapter 4, this chapter describes the more practical aspects of work analysis.

Chapter 6 narrows the thesis down even further, from analysis methods to knowledge elicitation methods. Because the core contribution of this thesis relates to the quality of such knowledge elicitation methods, this is a rather extensive chapter. The historic background of how knowledge elicitation

methods have evolved is presented, together with the pros and cons of each method.

Chapter 7 presents my own contribution to the task of knowledge elicitation. That is, the new method called collegial verbalisation (CV) that I have formulated and refined in my research. I describe how the method evolved, how the method is applied, as well as the overall results from different studies. Each of the research papers included in this thesis is presented separately.

Chapter 8 further discusses the findings of my research based on the results presented in Chapter 7. The chapter also raises some critique to the new method.

Chapter 9 directs the reader to some possibilities for future applications of the method. Such areas as risk assessment, team learning and applied system development are briefly discussed.

Table of contents

1 Introduction

The introduction of this thesis presents three important aspects that have served as a foundation for my research: (1) shared knowledge, (2) challenging work environments and (3) professional work.

1.1 Shared knowledge

Let's begin this thesis summary with an example from an everyday situation. Consider two parents and their 2-year-old daughter having breakfast. Both parents are reading a newspaper and the child is eating yoghurt by herself. When the child puts down her spoon on the table, both parents suddenly drop their newspapers, jump up from their chairs, bend over towards the child and reach for the glass of orange juice standing next to the bowl of yoghurt. So, what happened and why? Both parents, who were busy reading the news, implicitly perceived that their child had stopped eating. They anticipated that the child's next step would be to approach the glass and possibly spill the juice while attempting to drink. A person outside of the family would probably not have connected *"laying down the spoon"* with *"spilling orange juice"*. But the two parents had the same foreknowing about this, even though they never discussed it explicitly. It had simply become a routine for the parents based on their previous experiences.

Having foreknowledge about such things is rather common in our daily lives. It just happens without us reflecting on it. It's how our mind works. We learn many things implicitly without ever thinking or reflecting on them. This is a form of social learning.

Another situation where many people share environments and experiences is at work. In the same way as two parents start to think and act like each other, collaborating work colleagues tend to create shared thoughts and behaviours. The fact that people share knowledge with each other is an important foundation for my research. The way in which we use this shared knowledge is rather new within my research field. However, here is one example of another approach to use shared knowledge, but within a completely different research field. Djordjilovic (2012) studied authentic interaction in business meetings and performed conversation analysis of transcripts from these meetings. She focused on relations within and between managers and colleagues. In one study she found that subjects developed a shared team

identity by the practice of joint answering. Another study examined how co-leaders build shared identities and how colleagues develop reciprocal identities. She concluded that managers within the same company develop joint communication and therefore tend to behave similarly. This is a form of cultural learning. That is, an implicit process by which we are socialised to adapt to ways of thinking or behaving.
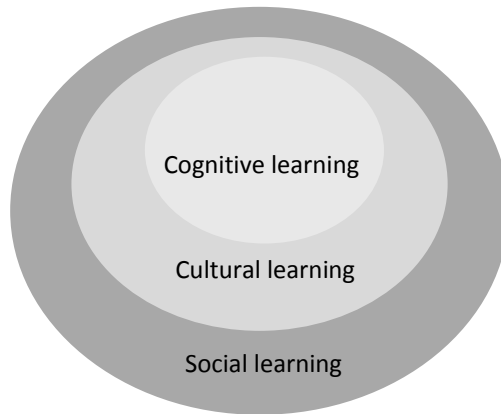
Figure 1: Illustration of the relationship between three forms of learning discussed in this thesis.

So far, we have discussed social and cultural learning, but there is a third form of learning that is more related to my own research. We can call it cognitive learning, and I will discuss this type of shared knowledge throughout the remainder of this thesis. Here is an example of this type of learning from one of my studies on-board high-speed ferries. Quoting myself,

"On-board the ship bridge, I once noticed that the captain gets eye contact with the first mate and then nodded vaguely, on which the first mate simply nodded back and nothing more seemed to happen after that. As an observer on the bridge, I could not tell what it meant. When the ship had berthed, I asked the first mate about it. He then explained that the nodding in this case meant that both himself and the captain understood that the approaching ship, which so far only was visible on radar but would soon appear behind an island, was positioned in such a way that they could not proceed through the fairway using the auto pilot. The nod therefore also inferred that he, as first mate, about ten minutes later, would have to disable the auto pilot and manually control the ship while passing the approaching ship and then return to the fairway and reactivate the autopilot."

The first mate did not consider this event to be anything worth further attention, but simply one way of how they communicated with each other on the bridge. Personally, I was astonished to learn that such a subtle sign could play such a highly significant part of the operators' communication, implic-

itly inferring the major navigation tasks on-board the bridge for the coming half hour. In the scope of this thesis the event implies two very important things. First, that the colleagues have a strongly shared mental picture of their work, and second, that it is difficult for an outsider to understand these implicit signs.

1.2 Challenging work environments

One of the strongest drivers in my career, both as an academic researcher and from working in a private product development company, has been to explore and understand specific work environments. I enjoy studying the challenges posed by different work contexts, which is one reason why I have chosen to study work environments that have a significant impact on the people working in it, such as vehicle operators.

Train drivers, high-speed ferry captains and train dispatchers have one thing in common: they all need to be able to make decisions in real-time while taking large amounts of complex information into account. A single inappropriate decision might cause an accident, which could affect the life of many people. The interfaces used to observe and control the system are often poorly designed for the performed tasks, thereby causing stress and reducing efficiency/safety. Work tasks that become more automated leave the operator to the task of monitoring rather than controlling. Monitoring operators who are less involved in controlling the systems become less alert. If an automated system fails, the operator is out-of-the-loop and will have difficulties in taking over the control of the system (Endsley, 1996). These are only some of the challenges that these operators can face in their daily work.

To obtain a better picture of the type of challenges vehicle operators face, let us now consider the full complexity of a specific work context. Based on my studies of high-speed-ferry operators, I present a brief description of its challenges. Consider a captain of a large high-speed ferry who is responsible for a 2000 metric ton ship with 1500 passengers travelling at a speed of 55 km/h in an archipelago. With the primary goal of safely reaching the next stop, the ship is controlled by a few bridge officers who 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 course or speed or if a new vehicle appears from behind an island. Therefore, the officers need to continuously plan to compensate for the ship's poor responsiveness.

The bridge officers' work typically consists of passive periods of monitoring intermixed with periods in which more intensive action is needed (e.g., at berthing). In a low traffic scenario the officers generally focus on monitoring tasks and planning as a way of remaining vigilant and reducing future burdens, but when navigating through crowded traffic (see Figure 2), the officers are faced with vast amounts of dynamic data. This data is con-

tinuously 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 the information on their computer systems in order to be able to navigate. A large modern bridge is a complex set up of electronics, including joysticks, buttons, knobs and at least 10 monitors with their individual controls spread over a large area. Different computer systems often have their own unique software requiring the officers to shift between many different forms of interaction depending on which system they are working on at present. This non-uniform set up can be quite dangerous when an officer is put in a stressful situation and forced to make quick decisions.

Imagine also 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, officers on other ships, 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 numerous sources, evaluating plans of actions in their head with little or no support and choosing and executing actions based on the integrated information.

Figure 2: Crowded traffic situation in Hong Kong harbour.

The challenging work environment described above is what Vicente (1999) refers to as a socio-technical system. Vicente's book list 11 characteristics of socio-technical systems in general, which here is presented in an abbreviated form:

- Many different elements and forces create large problem spaces
- Many people working together with a need for communication

- Heterogeneous perspectives of the workers complicate things, 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 interconnection between subsystems
- Automation forces the operators to deal with situations where automation fails
- Presented information might be erroneous. For example, caused by sensor failure or other random errors, thereby creating 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

Vicente's list summarises many of the problems associated with socio-technical systems in general. Looking a bit closer at the operator's task of controlling a system, we find other aspects that have a strong impact on the work, including the ability to observe and control the system and the way in which decision-making tasks are executed. Dörner (1996b) 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. Brehmer (1992) presents Edwards' (1962) classical description of dynamic decision-making tasks as having the following three characteristics: (1) they require a series of decisions, (2) these decisions are not independent and (3) the state of the task changes, both autonomously and because of the actions taken by people. Based on the experiences from Brehmer's studies, he also extends Edward's description with a fourth criterion: people have to act in real time. Furthermore, Perrow (1999), famous for his perspective on accidents, adds to this discussion by noting that all risky systems should have more quality control and training, but with respect to complexity and coupling, it will not be enough.

According to Brehmer (1992), four basic criteria need to be fulfilled for operators to have a chance of successfully performing their tasks: (1) there must be a goal, (2) there must be a model of how the system behaves, (3) it must be possible to ascertain the state of the system and (4) it must be possible to affect the state of the system (Figure 3).
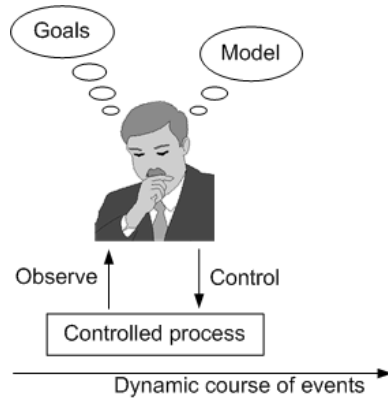
Figure 3: The four necessary conditions of control theory used to describe operators' abilities to operate a process successfully.

For example, large ships and trains have limited abilities to brake or make evasive manoeuvres. This would correspond to the aspect of control in Figure 3. Sometimes the effect of an action to control the system also might have a non-linear effect. Consider, for example, a train traffic controller doing some minor re-planning to optimise the traffic situation (Figure 4). In a crowded traffic situation changing the schedule for a single train might cause huge negative side effects later on or in an adjacent traffic region.

Figure 4: Train dispatchers busy controlling the traffic situation by 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.

To conclude, socio-technical systems have many challenging properties that together make it impossible to anticipate all possible ways that the system

can fail and therefore it is not feasible to create barriers that can prevent all possible accidents. However, by being aware of the challenging characteristics that prevail, it is possible to understand the problems that operators face and therefore also to improve their work situation.

1.3 Studying professionals at work

My research has concentrated on analysing the work of professional operators within the contexts described above. This rather specific scope is encompassed by the broader field of user experience (UX). Here follows an overview of this larger scope.

1.3.1 User experience

Throughout my years as a PhD student, there has been much confusion among researchers and professionals about how the different fields (e.g., human factors, interaction design and usability) relate to each other. However, a recent trend among HCI researchers and practitioners has been to both spread and accept the notion of UX as an encompassing field (Figure 5). Unfortunately, this is done without it being clearly defined or well understood (Law et al. 2009). The immense interest can be attributed to the fact that HCI researchers and practitioners have become well aware of the limitations of the traditional usability framework, which primarily focuses on user cognition and user performance in human-technology interactions. In contrast, UX highlights other aspects of such interactions, shifting attention to user affect, sensation and the meaning as well as value of such interactions in everyday life.

Figure 5: Illustration of how multiple disciplines contribute with different perspectives that together make it possible to improve the user experience.

1.3.2 Human-computer interaction

As a PhD student, I have been part of a Swedish research group at a department for HCI. My own research has focused on the traditional HCI aspects, including *"user cognition and user performance in human-technology interactions"* rather than *"user affect, sensation, etc."* (Law et al. 2009). Having emphasis on HCI aspects is quite natural when studying professional operators at work. Compare, for example, with a company developing computer games. Then user sensations become more important than traditional usability aspects. On the other hand, people working as train traffic dispatchers need work tools that properly solve their work tasks. By this, I am not stating that sensations and user affects are unimportant for train traffic dispatchers. On the contrary, I think there is a great potential to improve the train dispatchers work by encompassing the entire field of UX.

ACM SIGCHI (1992) 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."* To improve such *"interactive systems for human use"* many disciplines are involved, which makes the field highly interdisciplinary. 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"*.

With the intention of improving, for example, a vehicle operator's work in order to make it more enjoyable/interesting/efficient or less damaging to the operator's physical or mental health, some form of analysis, design and evaluation is needed. ISO 9241-210 (1999) describes a typical approach containing four fundamental activities that should be performed iteratively and starting early in the development cycle (Figure 6)
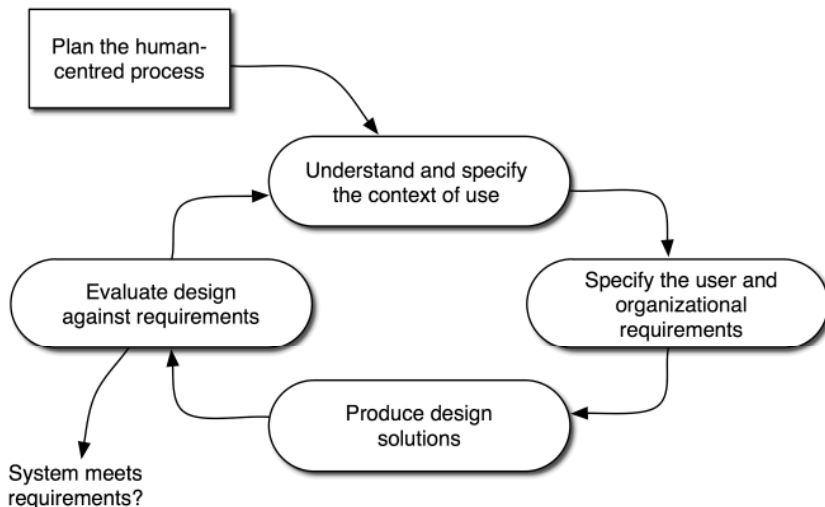

Figure 6: The iterative phases described by ISO 9241-210.

However, many practitioners within the field of HCI agree with Vicente (1999): *"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."*

1.3.3 Professionals at work

My primary motivation in this thesis is to improve operators' work environment and work situation in order to increase work safety and efficiency, as well as to improve the operator's work situation both physically and mentally. Within the scope of HCI, my research entails studying people in their professional roles at work. Put differently, I have primarily centred on analysis of work, rather than design issues.

I have worked within a research team at Uppsala University with a long tradition of studying cognitive work tasks. For example, Nygren and Henriksson (1992) analysed how physicians read medical records. Borälv et al. (1994) attempted to establish relevant design principles based on knowledge about cognitive aspects of HCI, as well as detailed knowledge of the specific needs within health care ward units. Olsson (2004) studied work analysis within several domains. She studied people working with case handling in office environments, dentists and medical staff use of medical records, train cab drivers and high-speed ferry operators.

Most of the work performed in our research group involves the challenging characteristics of socio-technical systems described in Chapter 1.2. Vicente (1999) describes socio-technical systems as consisting of an environment, organisation/management, workers and a technical system. He uses nuclear power plants and co-operative office work as typical examples of such systems. If such work challenges have to be meet under poor work conditions and in a poorly designed work environment, the situation can lead to health problems for the operators, as well as an increased risk of incidents or accidents. Far too often, accidents are blamed on the human operators rather than the poor work environment in which they are a part.

Within the HCI field, there is a primary focus on how to improve computerised systems so that they suit their respective users in their context. In my research I have studied professional vehicle operators and process operators and therefore my attention has primarily been on how to improve the computer systems that they use in their work. Such improvements have a large potential to increase work safety and efficiency, as well as to improve the operator's work situation at both the physical and mental levels. It is not necessarily the case that only the computer systems need improvements. Quite often, other aspects also need to be improved, including co-operation, leadership, work goals and demands. All these opportunities of improvement are a strong motivation for me personally.

If improvements in the work environment are 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 how they could work in the future. This thesis is about acquiring such an 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. For system developers to find out more about users work, they can study any available normative work description, such as instruction manuals, rulebooks and checklists. Such documents are often unambiguous and easy to relate to software development and therefore rather comprehensible to system developers. Unfortunately, they often fail to explain how the users actually work, but rather how management or former system developers want them to work or think they work. As long as one takes the information for what it is, studying this information should be better than having no information at all.

However, a more user-centred approach could involve interviewing users about how they work. Unfortunately, it is not very helpful to ask such questions as *"How do you work?"* or *"How do you perform the start-up procedure of your ship?"* Such questions often result in very shallow descriptions of the users' work. The answer might not even be representative for how the work is actually carried out.

Another solution is to use a retrospective verbalisation procedure, by letting the users describe their actions in video recording of their work. However, the users might recall things in the wrong order, forget important details, or simply believe that they do things in one way, whereas they actually perform the actions in a different way and therefore provide a misleading description (van Someren et al., 1994). These problems are especially relevant for highly automated work tasks that operators perform without much conscious reflection about their actions. Professional users adopt rather automated processes in their work, such that they have difficulties expressing their actions in words (Polanyi, 1974). One could of course complement such user interviews with observations while the users are working to ascertain that the interview results are reliable. Such complements could definitely improve the knowledge elicitation process.

1.4   Research question

It is a challenge to study the work of these operators. The operators are busy doing their job. If one disturbs them while they are working, the operators can lose focus on their tasks and possibly cause an accident. Another problem is that skilled operators have trouble expressing what they actually are doing, largely because their work tasks have become automated. If one lets

them finish their work tasks and ask them afterwards what happened, there is the risk they would tend to rationalise their own behaviour.

However, it turns out that there is an opportunity here related to the shared knowledge that I discussed in the beginning of this thesis. Things become intriguing when we combine our understanding that people who live or work together develop shared knowledge with the challenges of studying the operators' work in a socio-technical system. There is a potential to use the shared knowledge to acquire a better understanding of the operators' work.

The thesis now proceeds to define my research questions, based on the three aspects presented in the introduction (shared knowledge available among the professional operators, the challenging contexts of study and a strong focus on work analysis):

1. My research is based on the *theoretical assumption* that an ecological approach is possible. The usage context shapes the users' actions to a large degree, i.e. systems, structures, routines, etc., often limit the degree of freedom to choose different actions or make decisions. An ecological perspective can support the analysis of cognitive work tasks by taking advantage of the constraints in the usage context.

2. Based on the theoretical assumption, a new *methodological approach* is possible. Can some of the problems with traditional knowledge elicitation methods be overcome having a well-informed observer/narrator (a colleague) as a verbalising subject?

3. Based on the theoretical assumption and the new methodological approach, my research endeavours to make an *empirical contribution*. The CV method provides a new form of data source beyond traditional knowledge elicitation methods. What are the properties of this new data source? To what extent can this data source be used to better understand the operators' implicit work tasks and identify differences in the operators' understanding of situations and tasks?

1.5 Scope and limitations

First, my research is conducted within the field of HCI, and more specifically, I have focused on the analysis phase of the iterative design cycle. Within the scope of analysis, my focus is primarily on the task of knowledge elicitation. Hence, I have not put any emphasis on design or evaluation aspects, nor on the important aspect of doing all phases iteratively. Although my study of train dispatchers can be considered as much an evaluation phase as an analysis phase, this depends on whether one views the results as an assessment of the current system or valuable input to the next iteration.

Second, my research concerns skilled work. I have only studied professionals in their work. This thesis does not attempt to cover aspects related to users of walk-up-and-use systems such as ATMs and public websites.

Third, the professional users studied in this thesis work in complex sociotechnical systems, such as ship navigators and train traffic dispatchers. The new method discussed in this thesis (CV) has so far only been assessed in such highly technical domains and cannot generalise beyond that. However, there is no obvious known limitation of expanding the use into other situations involving professionals, such as administrative work.

The body of my research can be summarised as concerning knowledgeelicitation for the purpose of work analysis of skilled professionals in sociotechnical systems.

1.6   Short description of papers

This thesis includes seven research papers. The present chapter gives a brief summary of each paper together with a description of my own contributions to them. Figure 7 shows how the papers relate to each other and gives a good indication as to how my research has evolved. Roughly, my research can be divided into three phases: an insight phase in which vehicle operators were studied both in the laboratory and in the field; a method development phase in which I systematically defined and assessed the new knowledge elicitation method; and an application phase in which the new method is applied in different domains. Note that the three extensive field studies presented in Paper II, III and IV serve as basis for Paper V, VI and VII.
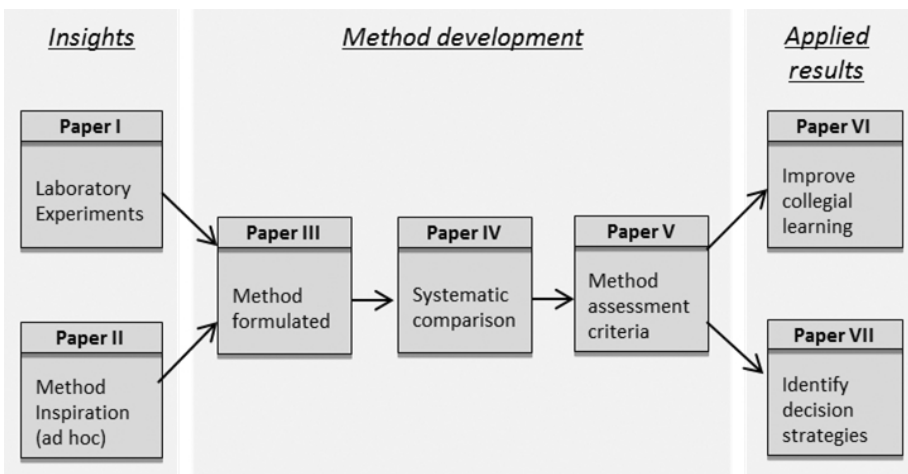

Figure 7: Relation between the research papers of this thesis.

1.6.1 Insight phase

My PhD research started with two rather different studies of vehicle opera-tors' work. The first study (Paper I) involved an evaluation of a novel user interface design for ferry operators performed in an experimental setting. The second study (Paper II) involved in-depth investigations of train drivers with a strong ecological focus. Hence, the studies had different purposes, were focusing on different phases in the design cycle and were employed in an experimental vs. a field environment, respectively.

Paper I - Augmented reality as a navigation aid for the manoeuvring of high-speed crafts

This paper presents the results from an experimental study of high-speed ferry operators. The purpose of the study was to evaluate the application of an augmented reality (AR) technique as a way of presenting sea chart and radar information to minimise the risk of data misinterpretation and therefore improve safety and reduce accidents. Among other things, the study indi-cated that the AR visualisation possibly affects both the operators' driving behaviour and attention. It also became apparent that the operators consid-ered *safe water* to be a relevant concept in line with how they think as com-pared with traditional visualisations, such as depth and fairways. However, the strongest effect from this study, which had significant consequences for my later studies, was the conclusion that there was a need for more real-world analyses as compared with experimental studies.

   My contribution to this study was to plan the experiments, refine the im-plementation of the graphical user interfaces to suit the experiments, co-ordinate the subjects during the experiments, analyse the results and write the paper. My co-author assisted me in formulating hypotheses, defining the experimental set up variables and providing feedback on the paper.

Paper II - Bridging the gap between analysis and design: Improving existing driver interfaces with tools from the framework of cognitive work analysis

This paper describes studies of train drivers. The research project was initi-ated before I started working as a PhD student and was first published by Jansson et al. (2005). The background was that we wanted to find methods to assess train drivers' knowledge as a basis for the design of new driver inter-faces in the train cabs. The first part of this paper describes observational studies and interviews with train drivers, as well as the first attempt to use colleagues as informants to examine the driver environment of passenger trains. Among other knowledge elicitation methods, colleagues were used as informants to get an additional observer's opinion about each target driver's actions. This study resulted in a fuller understanding of the work tasks of train drivers. More specifically, the study explained what kind of behaviour-shaping constraints the information environment imposes on train drivers.

The resulting data was 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 consisted primarily in setting up and executing the analysis using the CWA framework. The two studies and most of the contents of the paper were written by my co-authors. The results from this study served as a basis for Paper V, VI and VII.

1.6.2   Method development phase

The two studies described in Paper I and II shared the ambition to understand and improve the work of vehicle drivers. Based on experiences from experimental and observational studies, I chose to proceed with improving the promising idea of using colleagues as informants. The majority of my PhD work has been focused on the formulation and assessment of this new method.

Paper III - Collegial verbalisation – a case study on a new method on information acquisition

Paper III describes a study of high-speed ferry operators. Here, the method of using colleagues as informants (the CV method) was formalised into a new method in order to allow for reuse as well as scientific examination of the method. The purpose of this study was to understand in a better way what kind of information the CV method could provide. The resulting verbal protocols were compared to examine to what extent the colleagues agreed on the observed behaviour. The protocols from the colleagues allowed us to compare in-between the colleagues. The results showed that the colleagues not only had a shared view of the environment and the work tasks but also that they sometimes had discrepancies between them. This paper is the first of its kind to describe the method in detail and address it specifically.

My contribution to this paper was to utilise the method to study the work on board high-speed ferries (including planning, field studies, verbalisations, transcriptions and analysis). I also wrote most of this paper. My co-author assisted me in formulating hypotheses and provided feedback on the paper. The results from this study served as a basis for Paper V, VI and VII.

Paper IV - Verbal reports and domain-specific knowledge: A comparison between collegial and retrospective verbalisation

This paper describes a study of four train dispatchers in a train traffic control centre. The purpose of this study was to systematically compare the CV protocols with protocols from the more traditional method of retrospective verbalisation to gain a deeper understanding of the similarities and differences between the two verbalisation methods. Specifically, this study was performed within a project that focused on the evaluation of a new software tool

for planning and controlling train traffic in a region at a train traffic control centre.

My contribution to this paper was to apply the CV method in the context of train traffic control (including planning, field studies, verbalisations, transcriptions and analysis). I also performed the systematic comparison between the two verbalisation methods and wrote most of this paper. My co-author assisted me in formulating hypotheses, planning the experimental set up and provided feedback on the paper. The results from this study also served as a basis for Paper V, VI, and VII.

Paper V - Collegial verbalisation: The value of verbal reports from colleagues as subjects
This paper summarises the results from the three field studies: train drivers, high-speed ferry operators and train dispatchers (presented in Paper II, III and IV, respectively). Paper V also shows how the CV method evolved with examples from the three work domains. The paper also suggests a set of key principles that can be used to evaluate the new verbalisation method and hence allow examination of the method on a more theoretical level. This paper also suggests a new model distinguishing between different verbalisation methods (concurrent probing, immediate retrospective probing, long-term memory retrospective probing, long-term memory collegial probing and domain expert probing) in order to assess the methods on their degree of familiarity with the studied tasks.

My contribution to this paper was primarily the execution of two of the field studies (planning, field studies, verbalisations, transcriptions, analysis, and results). I also contributed to the formulation of the new model of verbalisation methods, and wrote most of the method and results sections of the paper. My co-author formulated the key principles and wrote a substantial part of the paper.

1.6.3   Applied results phase

After the CV method had been properly formulated and assessed in paper III, IV and V, my focus turned more too applying the method in different domains, rather than defining the method itself.

Paper VI - Collegial collaboration for safety: Assessing situation awareness by exploring cognitive strategies
Based on the previous three studies (presented in Paper II, III and IV) this paper promotes a discussion on whether collegial collaboration based on verbal probing procedures for knowledge elicitation of cognitive strategies is a good way to achieve resilience in socio-technical systems. The paper ends with a design suggestion of a more applied study that the authors plan to carry out and some preliminary results from a pre-study in an intensive care unit (ICU).

My contribution to this paper was to discuss and together with my supervisor determine how to apply the method in different socio-technical systems in general. We realized early that this method for knowledge elicitation also had the potential as a method for detecting differences in understanding between the participating narrators. When we got the chance to apply it in the in context of ICUs particularly, this was what we had planned for. The principal author wrote most of the paper.

Paper VII - Recognizing complexity – A prerequisite for skilled intuitive judgments and dynamic decisions
Based on the previous three studies (presented in Paper II, III and IV), this 7th paper shows how the new method can be used to analyse strategies used by decision makers in different types of complex real-time environments. The purpose of the study was to show how the method could contribute with a new form of data in this research context. The results demonstrate that decision makers use different time horizons in their attempts to control a process or a task. Such insights can help in identifying design principles for higher levels of automation, as well as to what kind of support one should aim for in terms of better user interface design.

My contribution to this paper was primarily the execution of two of the original field studies, including planning, field studies, verbalisations, transcriptions, analysis, and results. I also organised and performed the comparisons in an effort to find similarities and differences between the different work domains. We realized during the development of the method that it could be used for analysing decision-making strategies among operators and users in the different work domains we had investigated. The principal author wrote most of the paper.

2 Background

As stated earlier in this thesis, my main motivation is to improve the work environment and work situation for operators to increase work safety and efficiency, as well as to improve the physical and mental work situations of the operators. This is very similar to Vicente's (1999) three criteria for effectiveness (safety, productivity and health). Vicente argues that to design effective computer-based information systems that could facilitate work in complex socio-technical systems we need an understanding of what effective means, i.e. an explicit statement of the performance criteria that we must strive to satisfy is needed.

2.1 Safety

These three criteria (increased work safety, efficiency and operator health) are very important. I have seen a huge potential for improvement in all the work domains I have studied. Sometimes a simple adjustment to an operator's work tools would make a big difference. For example, I have sometimes seen operators doing unnecessary workarounds simply because the system does not allow them to do their job in the way it should be done. Having to do these workarounds can be frustrating and have a negative impact on the operators' mental health, but it is a way for the operators to gain control of the situation. However, the workaround might also reduce the safety of the system if it involves doing things in a way they were not intended for. The safety criterion is primarily mentioned in relation to industries that can cause large-scale catastrophic accidents (e.g., nuclear power plants). However, Vicente argues that other domains (e.g., the stock market) also need to consider safety. In this later case the risk is not primarily ecological or life threatening, but rather economic.

Let us consider a ferry operator involved in an accident. The operator is accused of driving too fast in the fog, even though he or she was only trying to maintain the timetable. In retrospect it is easy to say that it was wrong. Yet, who is responsible for giving the operators conflicting goals. How much pressure (by the company, his manager, his colleagues, and the passengers) is placed on the operator to follow the timetable? Does he get a lower salary this month if he does not reach the targets for on-time arrivals? Will he have

to leave his apartment if he cannot pay the rent this month? Should he have quit his job when he felt that he had to compromise safety concerns?

Within some domains (nuclear, flight and health care) there are examples of companies/organisations that have tried to enforce a different form of safety culture to avoid such problems (e.g., encourage the employees to complain if they identify potential problems). This situation is a good example of shifting focus from blaming the operator if something goes wrong to acknowledging the limitations of the socio-technical system. With such a safety culture, the company/organisation is much better equipped to improve safety.

2.2   Health

Health aspects can be difficult to measure. The extent to which a workplace is designed to induce health has an impact on quality of life as a whole, not only on the quality of working life (Reed, 1996). A classical miss-conception regarding health problems is that workers with a job that puts greater demands on them should experience higher level of stress, and thereby have a negative impact on their health. Karasek and Theorell's (1990) model clearly shows that it is not that simple. More important than the amount of demands is the amount of control that the individual workers have on the way in which they can deal with their job demands (Figure 8).
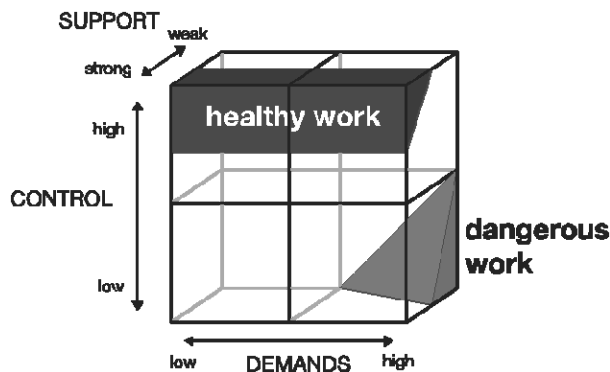

Figure 8: An illustration of Karasek and Theorell's demand control support model.

Operators can experience low control because they cannot address the problem themselves. They can also experience weak support because they do not get help with addressing the problem and experience high demands because they are still expected to perform their jobs successfully.

A work situation with obstacles that the operators cannot control themselves can be exceedingly stressful and unhealthy. Even if the operators try their best, there are often multiple conflicting goals that are impossible to fulfil simultaneously. For example, a ferry operator might strive to maintain a safe operation, keep the timetable and reduce fuel consumption.

Sometimes one can be impressed that there so few incidents or accidents given the unrealistic work situations. However, the tragic part in this story is the amount of accident investigations that conclude human factors as an attributed cause. See, for example, Hollnagel and Woods' (2005) illustrations of changes to attributed causes of accidents over a period of 40 years.

The search for human failure is the normal reaction to accidents. *"Formal accident investigations usually start with an assumption that the operator must have failed, and if this attribution can be made, that is the end of serious inquiry"* (Perrow, 1984, p.146). Because no system has ever built itself, because few systems operate by themselves and because no system maintains itself, the search for a human in the path of failure is bound to succeed (Hollnagel & Woods, 2005).

2.3 Productivity

The productivity criterion is naturally very important to any company exposed to competition. Landauer (1995) presents depressing statistics on how productivity growth has decreased since 1973. The author then argues that this is caused by the introduction of information technology in workplaces. Vicente reasons that business executives can easily appreciate and value the potential productivity improvement that can be achieved by addressing the issues of usefulness and usability.

2.4 Inevitable accidents

The strongest motivation to study operators is to prevent accidents. Some socio-technical systems (e.g., a nuclear power plant or an airplane) can have catastrophic consequences with many casualties or destroy the environment for decades. Other systems, such as a stock market, might have a significant economic impact. Unfortunately, accidents within socio-technical systems can never be avoided entirely. Perrow (1999) asserts that one cannot foresee the unanticipated interaction of multiple failures in a complex system. The author refers to this situation as *"normal accidents"*. Anyhow, because accidents in some socio-technical systems can have catastrophic consequences, it raises the ethical question of whether such system should be allowed to be constructed at all.

Socio-technical systems that have the potential of causing catastrophic events typically have multiple safety barriers to prevent this from happening. For example, the barriers of a nuclear power plant might involve multiple redundant systems to prevent significant radioactive release, comprehensive monitoring and regular testing to detect equipment or operator failures, solutions to confine the effects of severe damage to the plant, and an active safety culture to identify and correct potential risks.

Adding more safety barriers can reduce the risk of accidents as well as reduce the effects of the accidents that do occur. Unfortunately, accidents manage to occur regardless of the number of barriers that the system has enforced. Reason (1990) suggests that there is a *"limited window of accident opportunities"* when loopholes in each barrier happen to coincide. This phenomenon is more easily understood using the Swiss cheese model (Figure 9), which is commonly used within aviation and health care. The holes in the cheese slices represent individual weaknesses in individual parts of the system. These holes are continually varying in size and position in all slices.
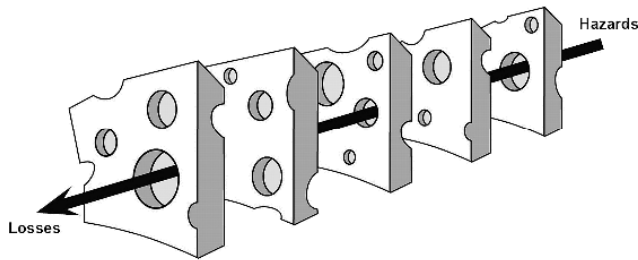
Figure 9: Reason's Swiss cheese model, illustrating how, e.g., an accident can occur when weaknesses in different safety barriers happen to coincide.

2.5 Automation

Many socio-technical systems rely heavily on automation to provide better performance, reduce cost and increase reliability. The improvement of introducing automation implies a dramatic shift in the operator's role. Instead of performing the tasks themselves, the operators monitor the actions of the system. Unfortunately, humans are not very well suited for this type of task (Endsley, 1996).

Figure 10: The plane wreck of flight TE901 with Air New Zealand in 1979.

Figure 10 depicts the crash site of the Air New Zealand flight TE901 in 1979. It was a New Zealand sightseeing flight in which the autopilot route of the airplane had been changed without informing the pilot (Perrow, 1999). Unfortunately, nobody on-board the plane noticed that this new route led straight into the Antarctic mountains until it was too late to take any evasive manoeuvres. Hence, one contributing factor to this accident was the properties of the automated navigation system, and the operators' poor ability to deal with automation.

Bainbridge (1987) submits that automation has a tendency to increase both stress and fatigue, mostly because the operator is left to do the tasks that automation cannot handle. Automation leaves the operator with long periods of inactivity combined with short periods of intense activity. Endsley and Kiris (1995) describe an operator caught in such a scenario 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 operator. The operator then has to switch from an inactive to an active state and perform the stressful task of acquiring an understanding the abnormal situation in order to take the 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 a problem of high mental workload.

A study of a large number of train accidents (Kecklund et al., 2001) found that most of the accidents had been preceded by a deviation from normal operating circumstances, and that stress and fatigue were contributing factors in roughly one third of the accidents.

Based on these issues with automation, Sarter et al. (1997) propose 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 (e.g., the critical times during a flight such as landing and taking off). Jordan (1963) summarises this nicely: *"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, on-going activities and system states and behaviours (Billing, 1991).

2.6 Situation awareness

The out of the loop problems with automation discussed in the previous chapter are strongly related to the concept of situation awareness (SA). Wickens (2008) states, *"as automation continues to be imposed in human work environments, there is little doubt that the interest in how SA may degrade or be supported will continue to grow"*. SA can be described as *knowing what's going on*. More formally, Endsley (1995) defines it as *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future"*. Sarter and Woods (1991) formulate SA as the *"accessibility of a comprehensive and coherent situation representation which is continuously being updated in accordance with the results of recurrent situation assessments"*. Endsley separates SA into three levels: perception (level 1), comprehension (level 2) and projection (level 3) (Figure 11).
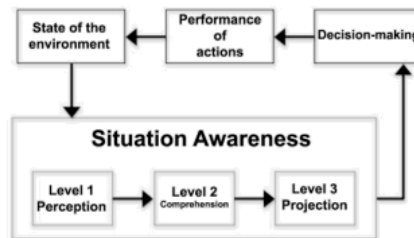

Figure 11: Endsley's model of situation awareness.

Achieving SA is one of the most challenging aspects of the operator's work; furthermore, it is central to good decision making and performance (Endsley, 1996). According to Hartel et al. (1991), poor SA was the leading casual factor in military aviation mishaps. Some critique has been levelled at SA, primarily questioning whether SA is an unnecessary construct above already existing elements (such as attention) (e.g., Dekker & Hollnagel, 2004; Dekker & Woods, 2002). However, it seems as though the practical use and need for the concept of SA serve as a testimony to its viability.

2.7 Mental models

Mental models are used here in a sense similar to the first description of it made nearly 70 years ago (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."*

Mental models are related to the knowledge level, referring to the highest level of skills, rules and 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."*

Cook and Woods (1994) refer to mental models as *"buggy"* when they are inaccurate or incomplete and can give rise to inappropriate actions. Knowledge of the world and its operation may be complete or incomplete and accurate or inaccurate. Practitioners may act based on inaccurate or incomplete knowledge about some aspect of a complex system or its operation. For example, Sarter and Woods (1995) identify buggy mental models as a contributing factor to mode error. If the operator has misconceptions of how the system works, this might have implications for the safety of the current system. It would be of considerable value to find such misconceptions in order to prevent them. To illustrate the strengths and weaknesses of mental models, I summarise the events of a rather well-known accident, namely the partial nuclear meltdown that occurred in 1979 at the nuclear power plant at Three Mile Island (TMI) in Pennsylvania, USA (Figure 12). As most accident investigations show, this accident was the result of a large number of contributing factors. However, here we will only elaborate on one of these factors, i.e. the operator's mental models of the system.

Figure 12: The nuclear power plants at Three Mile Island, Pennsylvania, USA.

Below, follows a brief summary of the events leading up to the accident. A relief valve to a pressuriser in the primary coolant loop of the reactor was stuck in an open position after automatically having reduced the pressure, with the result that some parts of the water inside the reactor started to boil, rather than remaining in liquid state under high pressure. At his point, the worker's mental model came into play. In the normal state of the plant, before the relief valve was stuck, the operators had a good understanding of how the pressuriser level indicated the amount of liquid water in the primary coolant loop. However, in the abnormal situation that had occurred, with the valve stuck in the open position, the pressuriser level was increased despite the fact that the amount of water actually had been reduced though the open valve. The operator naturally, but incorrectly, inferred that there was too much water in the primary loop and acted accordingly, an action that contributed to the partial meltdown that followed. It is worth noting that the operator's mental model had served them well for many years, and that this unique situation revealed the deficiencies of their mental model (Vicente, 1999).

2.8 Resilient systems

One promising approach to deal with the depressing conclusions about accidents in the previous chapters is called resilience engineering (RE). Hollan-

gel et al. (2006) define resilience as *"the intrinsic ability of an organization (system) to maintain or regain a dynamically stable state, which allows it to continue operation after a major mishap and/or the presence of a continuous stress"*.

Hollnagel et al. (2006) argue that a resilient system must have the ability to anticipate, perceive and respond. These three abilities are fascinatingly close to Diamond's (2005) analysis of how entire societies collapse. Diamond identifies three *"stops on the road to failure"*: The failure to anticipate a problem before it has arrived; the failure to perceive a problem that has actually arrived; and the failure to attempt to solve a problem once it has been perceived.

One of the characterising properties of RE is that safety is not considered a property that the socio-technical system has, but rather something that the system/organisation does. In other words, it is not a system property that, once having been put in place, will remain. It is rather a characteristic of how a system performs. This property of RE creates the dilemma that safety is shown more by the absence of certain events – namely accidents – than by the presence of something. Indeed, the occurrence of an unwanted event need not mean that safety as such has failed, but could equally well be because safety is never complete or absolute (Hollnagel et al., 2006).

Resilience cannot be engineered simply by introducing more procedures, safeguards and barriers. Rather, RE requires a continuous monitoring of system performance, of how things are done. In this respect resilience is equivalent to coping with complexity (Hollnagel & Woods, 2005) and to the ability to retain control.

3 Theoretical perspectives

Researchers use different scientific approaches to examine users' interaction with information technology. Different approaches of course end up with different types of result. Even if two researchers are studying exactly the same users in the same context, they often come up with different results, simply because they view the world with different sets of glasses (i.e. with different sets of beliefs, values and attitudes). To position the scientific approach of my own PhD research I will start by comparing it with other scientific approaches commonly used within HCI.

3.1 A controlled method approach

For an example of a controlled method approach, I use the field of dynamic decision making (DDM). In DDM simulated micro-worlds are used to study complex, dynamic decision-making tasks (Gonzalez et al., 2005). Specifically, DDM studies decision making that takes place in an environment that changes over time, either because of the previous actions of the decision maker or because of events that are outside the control of the decision maker (Brehmer, 1992), (Dörner, 1996a) and (Edwards, 1962). Broadly speaking, a micro-world is a small well-defined computerised game consisting of a limited logical world with complex interacting parameters. By letting subjects control different parameters of the simulation, psychologists are able to study human behaviour and decision making. The idea is to construct simulations that mimic the challenges of real-life situations. DDM studies complex decisions that occur in real-time and involve observing the extent to which people are able to use their experience to control a particular complex system, including the types of experience that lead to better decisions over time (Gonzalez et al., 2003).

For example, Jensen (2003) performed simulations of a predator-and-prey ecology to study non-professionals' abilities of reasoning, learning and taking decisions. Specifically, she used a simulation of rabbits and foxes. By letting subjects control different parameters of the simulation, psychologists are able to study human behaviour and decision making. Based on her studies, Jensen concluded that the subjects differ in their ability to transfer knowledge from the rabbits-and-foxes simulation to other tasks. She discusses her conclusion in relation to intelligence, level of math-education, etc.

The concept of micro-worlds is a good approach to acquire generalisable findings related to human decision making.

I appreciate the ambition of DDM to better understand human decision-making strategies and the way in which people learn from their experiences. Increased knowledge about this matter is indeed valuable in my field. My own research within HCI is highly dependent on such basic psychological research in human decision making. However, to be able to improve, for example, a vehicle operator's work situation a more realistic and applied research approach is required. The simulated micro-worlds are not able to capture the true decision strategies used by operators in their real work environments.

3.2 A simulator-based approach

One example of a more realistic approach to simulation than micro-worlds is found within the vehicle domain. Professional vehicle operators (drivers of airplanes, trains or ships) often need to do yearly training to retain their specific driving licence. A modern airplane cockpit simulator can be almost as realistic as driving a real airplane. For example, Alm (2007) uses airplane simulators to study visualisation and perception among aircraft pilots. Specifically, he tested the pilots' performance in symbol recognition and target heading assessments. Consequently, he is able to draw conclusions about suitable visualisations for the specific tasks of the pilot. Although this approach is more realistic than the micro-world approach, it is still limited because it is a simulation rather than the real world. Alm's thesis also confirms this argument when he describes negative effects caused by limitations to the simulation.

Pettersson (2008) also uses simulators. He examined how different three-dimensional (3-D) simulations affect the user's interaction. One domain studied by Pettersson was the safety critical field of military command and control, where it obviously is very important that any 3-D information is presented in such a way that it is not misinterpreted. The controlled experiments performed by Pettersson attempted to provide generalisable results on how people perceive 3-D.

In my PhD thesis I ask somewhat broader questions than Alm and Pettersson. Rather than determining whether certain types of visualisation are suited for specific control tasks for certain operators, the aim here is to learn about the operators' entire work situation, the entire socio-technical system, including, plans, goals, needs and organisational aspects. My more qualitative approach takes me further away from having well-defined measurable results, including statistical analysis. However, in my studies of train dispatchers some quantitative analyses were done to compare two types of verbal protocol. Some of the quantitative measures consisted in counting the number of topics in each protocol and the topics that had been previously

categorised qualitatively. This approach differs from the approaches of Alm and Pettersson. Their experiments were set up to provide measurable data directly from the experiment, without requiring intermediate qualitative analysis.

However, this thesis actually does include a paper (Paper I) that involves an experimental design in which experiments with 3-D simulations of high-speed ferry operators were performed. A simulator was used to examine how the usage of AR could aid the operators of high-speed ferries in the task of navigation in scenarios with low visibility. However, the bulk of my PhD work is not based on a simulator approach, but rather on a more ecological approach.

A simulated experiment does not capture the complexity of the real world. For instance, in the case of train dispatchers a handful of different conversations can take place simultaneously between 10 and 15 people who work in the control room. There is risk of disturbances, mix up and confusion, but also over hearing each other's conversations and helping out. Such commotion is normally not included in simulated experiments. A train dispatcher might go to the toilet after a few hours of work. Perhaps his neighbouring colleagues cover for the dispatcher, if they are not busy. What happens if something goes wrong on the dispatcher's control area during the short absence? How does he deal with it when he gets back? This would be a completely normal situation that would not likely be covered in a simulated experiment. Therefore, comprehensive, ecological approaches are needed.

3.3   A theoretical concept approach

Another experimental approach has been used by Alfredson (2007). However, the starting point in his thesis is not so much the simulations but the theoretical concept of SA. Alfredson's goal was to improve the SA of pilots and thus he performed different experiments to achieve that goal. He discusses shared SA and introduces the term *situation management* to extend the concept of SA.

Alfredson's approach, to focus on a single theoretical concept, is worthy because it gives his thesis a very clear focus and goal. The importance of SA in socio-technical systems is very strong and hence Alfredson's efforts to improve it are obviously very meaningful.

My own approach does not start with a theoretical concept. Rather, I use the theoretical concepts I find relevant in my own research. However, like Alfredson, I perform studies of vehicle operation and I find SA to be a very useful concept. Chapter 2.6 presents a more detailed presentation of this subject.

3.4 An ethnographic approach

In contrast to the experimental approaches and the theoretical concept approach discussed above, this section describes approaches of a more ecological nature. Ethnography involves the long-term deep field study of humans. Ethnographic field research is performed using a holistic perspective, with strong focus on being self-reflective of one's own analysis (Ember & Ember, 2006). The results often include deep descriptions and analysis of the environment under study and the social life of the humans who are active within it. Observations are supposed to be made from the point of view of the informants, not the observer.

Ethnographic data collection methods are meant to capture social meaning and ordinary activities of people in naturally occurring settings (Brewer, 2000). The goal is to collect data in such a way that the researcher (observer) imposes a minimal amount of his or her own bias on the data. Multiple methods of data collection may be employed to facilitate a relationship that allows for a more personal and in-depth portrait of the informants and their community. Ethnographic methods can include participant observation, field notes, interviews and surveys.

For example, Hutchins (1995) performed ethnographic studies on-board navy ships. He submits that many foundational problems in cognitive science are a consequence of researchers' ignorance of the nature of cognition in the wild. Most knowledge of cognition was learned in laboratory experiments, but little is known about the relationships of cognition in the captivity of the laboratory to cognition in other kinds of culturally constituted settings. I fully agree with Hutchins about the need to study cognition in the real world.

Lützhöft (2004) performed ethnographic studies on-board ship bridges. She carried out longitudinal observations and interviews, analysing the results qualitatively. Lützhöft emphasises that focus needs to be on cognitive tasks rather than on engineering and devices.

Although I do not follow a strict ethnographic approach, my research has many similarities with it. For example, my research aims to understand the operators' daily work in their normal work environment. But rather than doing the observations myself from an informants point of view, I strive to use colleagues as analysts to learn about the environment.

3.5 A conversation analysis approach

There are of course other ecological approaches than ethnography to study the cognitive work of professional users. Another qualitative approach is to perform conversation analysis. Djordjilovic's (2012) studied authentic interaction in business meetings and performed conversation analysis. She evaluated relations within and between managers and colleagues. In one study she

found that subjects developed a shared team identity by the practice of joint answering. Another study examined how co-leaders build shared identities and how colleagues develop reciprocal identities. She reached the conclusion that managers within the same company develop a joint way of communicating and therefore they behave similarly.

Djordjilovic aimed to acquire a deeper qualitative understanding of her subjects and her thesis presents and discusses the results accordingly. Djordjilovic's approach to compare how different colleagues think and act parallels my own research. She identifies similarities and differences among colleagues, arguing that the social context shapes the colleagues to behave similarly. This view corresponds closely with my own research results. I often emphasise that the environment shapes colleagues to act and think similarly. In the rather technical domains of vehicle operation, it is easy to think of how the properties of a certain work tool causes the drivers to think similarly about how to, e.g. change the speed of the train. For example, there is a delayed effect when adjusting the speed lever in a train cab that is caused by physical properties of the train and its braking system. Through experience, the train drivers acquire a feeling for how the speed lever affects the train speed. Most train drivers develop a similar feeling and therefore the technical system can be said to shape how the operators think and act.

In that perspective Djordjilovic's (2012) studies are somewhat different. Her results emphasise that colleagues think and act similarly because of the social situations in which they work. She focuses more on group dynamics and team formation. I consider these social aspects to be of equal importance to the more technical aspects in my example above and my research would benefit from acknowledging the social side more.

3.6 A cognitive ergonomic approach

Yet, another ecological approach to study the work of professional users was applied by Dutarte (2001) and Barchéus (2007). The authors studied cognitive aspects within the socio-technical system.

Barchéus studied communication, co-ordination and collaboration in air traffic management systems. He performed observational studies from simulations as well as from the field, complemented with questionnaires. His research resulted in detailed knowledge about the specific cognitive aspects of air traffic management. He also noted that it is generally acknowledged that a large part of system failures are caused by, or contributed to, human factors (Danaher, 1980; Amalberti, 1993; Greatorex & Buck, 1995). Organisational systems are also known to create conditions that may retain errors within systems (Dörner, 1996b). The fact that there are many embedded failures, or latent conditions (Reason, 1990), in large complex systems may be seen as one of the most basic arguments for having human operators *"at*

the sharp end" of operations. The human operator allows flexible handling of situations that have been omitted by the designer.

Dutarte performed interviews, field observations and used questionnaires to acquire detailed knowledge of steering and navigation on-board ships and aircrafts. The primary contribution of Dutarte's thesis is the descriptions of how the tasks are carried out presently and the suggestions of potential improvements for work systems in future transportation systems. Dutarte emphasised the need for a cognitive approach by quoting Hancock (1996). *"Human society is engaged in a perilous endeavour with respect to technical systems. Human factors currently takes technology as given and seeks to facilitate interaction, assuming technology to be a good thing. But is it so? To become more than just an appliance science, human factors should focus directly on the issue of why technology is used – its purpose – in addition to how technology is used – its practice."*

My research is comparable with Dutarte and Barchéus in the sense that my aim is to study cognitive work in similar domains (vehicle operation and traffic management). However, the primary focus of my research has not been to describe the specific details about the cognitive work in these work domains, but rather to improve ways to study the cognitive work itself. Specifically, this has been accomplished by developing a method for knowledge elicitation that makes it possible to study professionals in the field in a more clear and comprehensive manner. Hence, the most obvious difference between all the research approaches discussed above and my research is that I concentrate on method development.

4 Theoretical approach and research design

Following the short presentations made in Chapter 3 of different research approaches, I will now proceed to define my own standpoint more exhaustively. This chapter starts with defining my epistemological view, followed by a description of how my research is grounded in ecological psychology and CWA.

4.1 Views of knowledge

This thesis strives to improve the act of knowledge elicitation when studying professionals at work. To clarify what I mean with knowledge elicitation I must first define my view of knowledge and here specifically professional expertise.

There are many views on knowledge. First, we need to separate knowledge, information and data. The classical DIKW pyramid (Ackoff, 1989) separates data (facts without relation to other things, e.g., *"107"*), information (processed data that includes some form of relationship, e.g., *"107 years old"*), knowledge (a pattern that could predict events, e.g., *"107-year-old people have a high probability of dying"*) and wisdom (Figure 13).
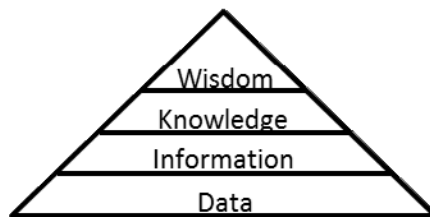
Figure 13: The DIKW pyramid distinguishing between data, information, knowledge and wisdom.

Around 1980, an epistemological controversy occurred between quantitative and qualitative research fields. Guba and Lincoln argued in several influential papers (Guba & Lincoln, 1994), (Lincoln & Guba, 1985) that the appropriate epistemological paradigm for qualitative research was constructivism. This view is the position that our understanding of reality is a social construction, not an objective truth, and that there exist "*multiple realities*" asso-

ciated with different groups and perspectives. Lincoln and Guba (2000, p.168) termed this a *"relativist"* and *"transactional/subjectivist"* position, in opposition to views that were variously labelled positivist, realist, objectivist, or empiricist; the latter positions *"assume the possibility of some kind of unmediated, direct grasp of the empirical world and that knowledge simply reflects or mirrors what is 'out there'"* (Schwandt, 2007).

My own journey within academia started out in the natural sciences, specifically computer science programming. The logic and structure of mathematics and programming were combined with quantitative methods during my master's program, until the third year when I took my first course in HCI. There was a good deal of confusion, frustration and lack of trust among the more hard-core programming students when our HCI teacher encouraged the class to perform user interviews. The qualitative data that resulted from these interviews were hard to interpret and consisted of conflicting data that made it difficult to draw trustworthy conclusions.

Personally, I felt that this was the first course of the master's programme where my student project had a connection to something meaningful in practice. The outcome of our assignments could actually make sense for real people. It is of course still relevant to run programming courses with the purpose of letting the students explore and learn a new programming method, without requiring it to be directly applicable. However, by starting out from a real user need rather than from a technological standpoint, gave me a good feeling of having a connection with reality. This also meant that I shifted attention from low-level programming of compilers and operating systems to focusing more on user interfaces and user needs.

When I started as a computer science student, I accepted the traditional positivistic view of knowledge without any particular reflection. The positivistic approach has indeed been successful in increasing society's level of knowledge about physical phenomena (e.g., gravity). Positivism assumes that there is valid knowledge (truth) only in scientific knowledge and considers information derived from sensory experience, logical and mathematical treatments of such data as the exclusive source of all authoritative knowledge. Obtaining and verifying data that can be received from the senses is known as empirical evidence. This view holds that society operates according to general laws like the physical world (introspective and intuitive knowledge is rejected).

After my introduction to HCI, it didn't take long before I realised that my positivistic approach was unable to capture the real value of user needs. Schön (1983) described professional practice as having properties of uncertainty, instability, uniqueness, complexity and value conflict. By applying the scientifically well received method Fitts' Law (Fitts, 1954), I obtained results about the interaction of our target users. However, at the same time, the method reduced the problem to a single variable: the time it takes to point at something with, e.g., a mouse or a finger. Although it might be a

relevant aspect in some situations, it does not tell us much about the usability of the system as a whole (Beaudouin-Lafon, 2004).

Because the connection with user needs drove me towards HCI in the first place, I simply had to accept the less generalisable forms of knowledge that is the result of using methods such as interviews and direct observations. Simply put, I gladly traded the generalisability of my results to be able to create value for specific groups of users. This position does not mean that I reject quantitative methods; on the contrary, I think they are highly valuable and I try to use them wherever they can be used successfully. However, to understand and improve on the tasks, tools and needs of users quantitative methods are not enough.

4.1.1 Constructivism

I have the ambition to understand the users' actions, needs, goals, challenges and motivation in their real work practice. To deal successfully with this research task I have chosen an empirical and holistic research approach based in a constructivist framework. 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 their actions in the world (Fenwick, 2000).

Constructivism is based on the work of Piaget (1952). Meaning is constructed based on experiences. Even though we hear and receive information, it does not necessarily mean that we have learned that information. New learning is assimilated into the learner's mental schemas by connecting with knowledge that already exists. New information that does not fit into the schema is hard for the learner to understand. Meaning must be made by connecting the new learning to the old and new learning must be reflected upon and connected with old experiences. Learners must reflect upon learning to make it connect to the old learning and to construct it's meaning. Learning is done mainly by asking questions, exploring and evaluating what is known. Each of us generates our own rules and mental models, which we use to make sense of our experiences. Learning, therefore, is simply putting the process of adjusting our mental models to accommodate new experiences.

Piaget (1952) proposed a mechanism by which infants integrate experience into progressively higher-level representations. According to constructivism, infants progress from simple to sophisticated models of the world by use of a change mechanism that allows the infant to build higher-level representations from lower-level ones. Constructivism is a powerful model of grounded knowledge acquisition that has been applied to grounded knowledge acquisition tasks with considerable success (Drescher, 1991; Cohen et al., 1997). Knowledge is created in social interaction between investigator and respondents and the results or findings are literally created as the investigation proceeds (Guba & Lincoln, 1994).

4.1.2 Expertise

Another important distinction relating to knowledge is made by Rasmussen's SRK taxonomy. The SRK framework defines three types of behaviour or psychological processes present in operator information processing (Vicente, 1999). In the broader sense, I consider all three levels (skills, rules and knowledge) as different types of knowledge. Within the SRK taxonomy, the term knowledge relates to more advanced levels of reasoning (Wirstad, 1988). The knowledge level of reasoning is employed in novel and unexpected situations. Because operators need to form explicit goals based on their current analysis of the system, cognitive workload is greater than when using skill- or rule-based behaviours.

Rule-based levels of reasoning are characterised by the use of rules and procedures to select a course of action in a familiar work situation (Rasmussen, 1990). The rules can be a set of instructions acquired by the operator through experience or given by managers or colleagues. Operators are not required to know the underlying principles of a system to act on a rule-based level.

Skill-based level of reasoning requires very little or no conscious control to perform or execute an action once an intention is formed (also known as sensorimotor behaviour). Performance is smooth, automated and consists of highly integrated patterns of behaviour (Rasmussen, 1990). For example, bicycle riding is a skill-based behaviour in which very little attention is required for control once the skill is acquired. This automaticity allows operators to free up cognitive resources, which can then be used for higher cognitive functions (Wickens & Hollands, 2000).

The process of going from novice to expert involves level-like qualitative shifts (Adelson, 1984; Phelps & Shanteau, 1978; Spiro et al., 1989). With practice, a skill loses the quality of being conscious, effortful, deliberate and linear, taking on instead the quality of automatic pattern recognition. In short, judgments become *"intuitions"* in that one can rapidly and effortlessly associate experiences, make decisions or perform actions. The expert can often tell you the decision, i.e. 'what', but not describe the process, i.e. the details of 'how'. Expertise is difficult to teach and to describe. Experts use it without knowing what they are doing, but are still confident that their methods are effective.

The concepts of knowledge and expertise defined above are fundamental with respect to the knowledge elicitation represented in this thesis. Chapter 6 contains an in-depth discussion of knowledge elicitation.

4.2 Ecological psychology

I have based my research in the research tradition of ecological psychology. There are many established research perspectives dealing with human ac-

tions in complex and dynamic systems, of which only some recognise the impact of the environment. Studying operators working within a socio-technical system requires an approach that deals with the complexity of their real world.

Ecological Psychology emphasises the importance of the environment, specifically the direct perception of the humans (Gibson, 1966). Gibson suggests that to explain some behaviour in an adequate fashion it is necessary to study the environment in which the behaviour took place and especially the information that connects the organism to the environment. Quoting Mace (1977), *"ask not what's inside your head, but what your head's inside of"*.

Psychology and HCI have a lot in common regarding how the two disciplines developed into two independent sciences. Psychology, on the one hand, struggled in the late 1800s and early 1900s to emerge as a laboratory science to distance itself from philosophy. Quite successfully, experimental psychology contributed to the establishment of psychology as a scientific discipline separated from philosophy. However, this pushed psychologists into controlled observations and experiments to the degree that they dismissed informal experience and complex environments in that these were seen as too chaotic to study and analyse. Among other things, this imposed a rather rigid approach to the study of human perception. Visual perception occurs as humans and objects move about in the physical world. When observers move around, the visual information is dynamic. For example, consider driving a car. The environment around you changes in size and position as you travel forward along the road. The dynamic relations in the information through time are critical to how we are able to see the world, and these critical dynamics depend on the optical richness of real objects (Carroll & Rosson, 2003). These insights founded the ecological approach to visual perception, which is the core of ecological science. *"Ecological science rests on the principle that systems in the natural and social world have evolved to exploit environmental regularities"* (Carroll & Rosson, 2003, p.439). The ecological perspective was pioneered by the work of James Gibson (1950; 1966; 1979) and Egon Brunswik (1956). Below, these two approaches are described in more detail.

HCI, on the other hand, borrowed many of the controlled observation methods from experimental psychology during the early days of human-machine interaction and ergonomics. HCI became one of the first established cognitive sciences. Newell and Simon's (1972) work on human problem solving and the Information Processing (IP) model became the main paradigms not only in psychology but also in the field of HCI.

It is worth pointing out that I do not attempt to cover the entire ecological psychology tradition here, only enough to position my research in relation to it. I have a more applied aim, which is to take my starting point from the later work by Rasmussen and Vicente. Hence, some of my usage of traditional terminology within ecological psychology is used in a more applied

manner than its original use. From a practical point of view, terms such as mental models and affordances are of great value. In fact, I use the term affordance without necessarily adopting Gibson's view that affordances are directly perceived by an individual instead of being mediated by mental representations (such as mental models). On the contrary, I acknowledge mental models as an important concept.

The Danish engineer, Jens Rasmussen, was one of the first to question the development of the IP model. Rasmussen and colleagues had been conducting field studies of electronic trouble-shooting strategies (Rasmussen & Jensen, 1973) and cognitive activities of professional operators during the start-up of a conventional power plant. Based on these studies, he found that existing theories were inadequate to explain his results.

In their field studies Rasmussen and co-workers used verbal protocols as their main data source despite that such reports were considered unreliable by many psychologists at that time. *The electronic trouble-shooting field study was important because it showed that expert strategic behaviour in a representative setting could be described systematically, despite its apparent complexity* (Vicente, 1999, p.363). This citation describes quite well the ambition of Rasmussen and Vicente to study and analyse the complex work performed by experts in order to be able to describe it systematically. The resulting descriptions become irreplaceable knowledge as input to a design phase if one is to develop a new system or change an existing one.
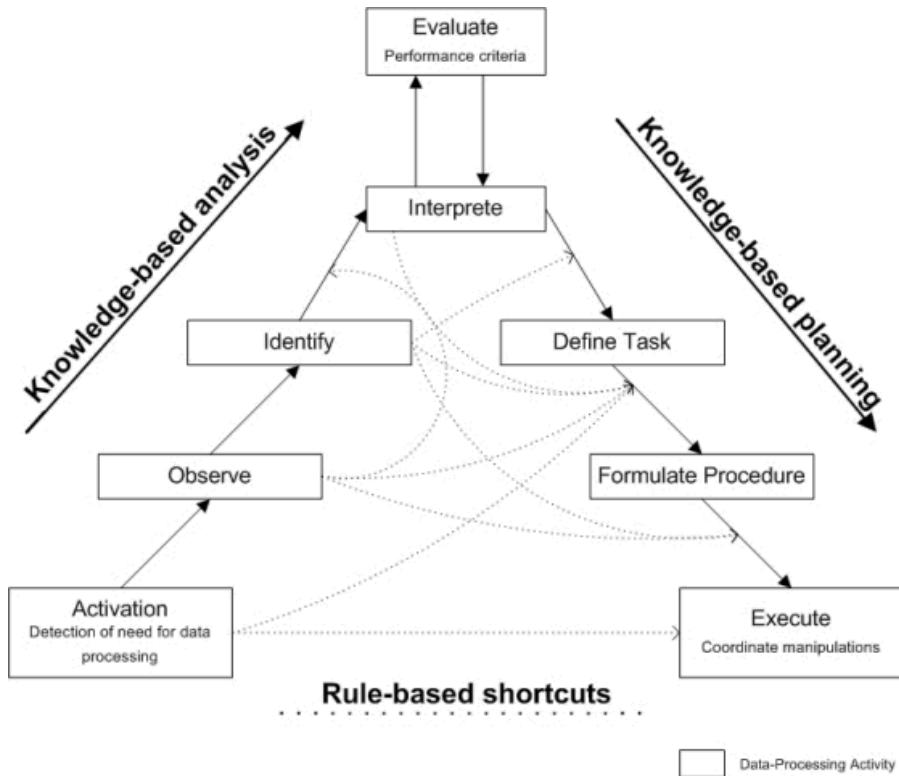
Figure 14: Simplified version of Rasmussen's (1983) decision ladder

The field study of the cognitive activities of operators was important because it became the empirical foundation for the decision ladder (Figure 14), a conceptual framework representing the information-processing activities that occur in human decision making. *"This eventually led to the skills, rule, knowledge (SRK) framework (Rasmussen, 1983), which categorizes three qualitatively different ways in which people can interact with the environment"* (Vicente, 1999, p.364). As in the case of the ecological approach to visual perception, the seminal work of Rasmussen sheds light on the importance of studying both the task characteristics and the psychological mechanisms in explaining human behaviour. It does not matter whether the tasks consist in natural perceptual tasks or human behaviours in socio-technical systems.

Inspired by ecological psychology in general, but also by the work of Gibson (1950; 1966; 1979), in particular, Rasmussen developed the abstraction-decomposition space (Rasmussen, 1979; 1985). A two-dimensional modelling tool, that can be used to conduct work domain analyses in socio-technical systems (See example in Table 3, Paper I).

"Gibson showed that perception in movement permits direct recognition of higher-order optical properties such as the expansion pattern one sees in

approaching a textured scene or surface. Gibson concluded that real-world perception typically consists of direct recognition of complex properties he called 'affordances'. This contradicted the most fundamental assumption of perceptual psychology at that time, namely that higher-order properties, such as being an object or being something that can be poured, are inferred on the basis of piecemeal recognition of local features like contours, edges, and angles" (Carroll & Rosson, 2003, p.440). Gibson proposed that the environment should be analysed in relation to the specific accompanying information in the environment that humans could detect. This innate information of the environment later became a very popular concept within HCI (today, under the name of *"affordances"*). In Hutchins' terms affordances is the real, perceivable opportunities for action in the environment, which are specified by ecological information.

Gibson's research on direct perception is highly relevant in my research on vehicle operators. There are many critical situations where direct perception and affordances can be vital to a vehicle driver. In my research I have found several such examples. However, the aspect of direct perception is only a limited part of the operators' complex work tasks. More cognitive and long-term aspects also need to be considered (e.g., the drivers' goals, plans and strategies, as well as social and organisational aspects).

"Brunswik showed how some of the most perplexing perceptual phenomena identified and investigated with line drawings, like visual illusions, could be explained in terms of the ways objects align and occlude in the physical world. He suggested that a basic method for perceptual psychology should be ecological surveys of the real world" (Carroll & Rosson, 2003, p. 440).

To summarise, the pioneering work of Gibson and Brunswik have influenced my own research in several ways. First, Gibson's work inspired me to use his idea of affordances as a practically meaningful concept, without adopting his idea that an individual directly perceives affordances without being mediated by mental representations. Second, Gibson influenced Rasmussen's research, among other things, to develop the abstraction-decomposition space. Hence, Gibson indirectly influenced my own work that is grounded in Rasmussen's CWA framework. Brunswik, on the other hand, influenced how I developed my methodological research approach. As co-founder and advocate for the ecological psychology approach, Brunswik argued that examination of problem solving and decision making should be executed in representative environments. Such a view is a key aspect that my own research tries to address.

4.3   HCI as an ecological science

With my theoretical approach grounded in ecological phycology, the next step is to discuss how HCI is applied in an ecological manner. HCI largely

concentrates on improving existing computer systems or invent new ones, and thereby improves the users' situation. An ecological approach to these HCI-tasks would typically involve in-depth studies of the environment in which the system is to be used and then use that knowledge when designing a new system. However, by introducing the new system in the environment, the users' tasks will change, which means that new user studies of the environment are needed. Carroll and Rosson (2003) refer to this as the task-artefact cycle (Figure 15).

New possibilities or
constraints of use

Tasks   Artefacts

New requirements as a result of
revised or changed tasks
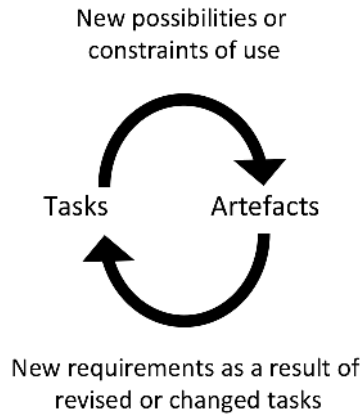
Figure 15: The task artefact cycle (Carroll et al., 1991).

Carroll and Rosson (2003) also suggest that HCI can be developed as an ecological science at three levels: taxonomic science, design science and evolutionary science. Carroll and Rosson specifically focus on design rationales. A design rationale is an explicit documentation of the reasons behind decisions made when designing a system or artefact. For example, a computer system does not itself express the motivations that initiated its design, the user requirements it was intended to address, the discussions, debates and negotiations that determined its organization, the reasons for its particular features, the reasons against features it does not have, the weighing of trade-offs, and so forth. This information comprises the design rationale of the system.

The first level at which HCI can be developed as an ecological science is the *taxonomic level,* involving the task of carrying out some form of classification of the object of study. Carroll and Rosson propose that when using design rationales as design documentation they are consistent with Brunswik's (1956) notion of ecological surveys. An ecological survey is a natural environment study of the way things are in the everyday world. Brunswik described the layout of the actual objects in the world, and a design rationale approach provides an inventory of the components and rela-

tionships in systems and software. It identifies potential consequences and trade-offs associated with designs and design features.

Second, ecological surveys of design practices provide the raw material for what might be called a *design science* of HCI. The idea here is that descriptions of particular designs can be abstracted and generalized by categorising designs and the features that define the categories can be associated with general consequences for users and their tasks. This idea is similar to those ideas behind the development of micro-worlds in the field of decision making (see, e.g., Brehmer & Dörner, 1993). The micro-world approach is a further attempt to develop the ideas of Brunswikian psychology.

Finally, also an *evolutionary science* to design can be seen as a branch of ecological science. Designs react to a perceived state of affairs (i.e. tasks that people want to accomplish, distractions they want to avoid. etc.). *"When a new artifact is designed and introduced into a given state of affairs, it changes things, i.e. some tasks become easier to carry out, some other tasks more difficult, some tasks become unnecessary etc. Tasks and the context of carrying out tasks create needs and opportunities for new artifacts, but those new artifacts consequently alter the tasks and eventually create new needs and opportunities for further designs. We call this the task-artifact cycle"* (Carroll & Rosson, 2003, p. 441). Consequently, the evolutionary aspect of ecological science concerns the understanding and management of trajectories of changes in the task-artefact cycle (Figure 15).

4.4 Cognitive work analysis

The CWA framework was developed to model complex socio-technical work systems (Rasmussen et al., 1994) (Vicente, 1999). CWA differs from other approaches to work analysis with its emphasis on constraints. Rather than trying to describe how work is performed (descriptive) or should be performed (normative), CWA seeks to identify intrinsic work constraints (a formative approach); i.e. it identifies both technological and organisational requirements that need to be satisfied if a device is going to support work in an effective manner.

Vicente suggests the use of field descriptions to capture the intrinsic work constraints. A field description is similar to a traditional map of a region. Consider navigating in your normal environment using a map vs. a set of directions. The map describes the *"lay of the land"* independent of any actor or actions on that land, whereas directions describe activities that should be performed to reach certain locations. With the map, it is possible to navigate even when one has gotten lost, need to make a detour or have a different starting point than normally. Similarly, a work domain representation or field description describes the structure of the controlled system independent of any particular worker, automation, event, task, goal or interface, whereas a task representation describes what goals should be achieved and perhaps

how as well. Just as maps allow people to deal with novelty, a work domain analysis allows people to cope with the unanticipated (Vicente, 1999).

Already in the 1930s, Gibson and Crooks (1938) realised that behavioural constraints could be identified by describing the functional possibilities of the work domain rather than tasks. Their studies of car drivers resulted in field descriptions that represented the possible paths that a car may safely follow. This example is very close to my own studies and the intrinsic constraints of professional vehicle operators.

While on field studies I have seen that the operators use their work tools in a way not intended by the system designers. They do whatever workarounds that are needed in order to be able to do their job properly. Some workarounds might of course have a negative impact (e.g., on safety). By giving the operators relevant boundaries within which they can act, rather than rigid task lists that they should follow, I believe the need for doing such workarounds should be reduced.

The most important value of CWA is its ability to account for events that were not anticipated by the system designers. It might seem to be a contradiction to be able to design for unanticipated events. Such events are the ones that designers cannot design for, even if they wanted to. CWA's approach to this is again connected to the boundaries. The foundational assumption is that operators in a complex system operate with a large number of capabilities and within a large number of constraints. The operators remain free to employ these capabilities as they act flexibly within the constraints. Therefore, they are free to adapt to unanticipated situations. The purpose of CWA is to identify and map out those capabilities and constraints.

CWA also emphasises how knowledge about ecological vs. cognitive aspects should be treated in the work analysis process. Studying sociotechnical systems, humans and machines imply certain constraints that have to be acknowledged and dealt with on an effective basis. The CWA framework suggests that ecological constraints should be identified and considered before moving towards aspects that imply more cognitive constraints (Vicente, 1999). The field descriptions discussed here are part of the initial phase (called work domain analysis) of the CWA framework. Vicente uses the abstraction-decomposition space discussed earlier to perform this type of analysis.

4.5 Other ecological approaches

There are many other ecological approaches, in addition to CWA. I have not worked explicitly with these approaches, but I am sure their ecological focus has influenced me in some way or another. I present them here because they provide a complimentary perspective, directly or indirectly.

4.5.1 Situated cognition

Within situated cognition, Brown et al. (1989) claims that knowing is inseparable from doing by arguing that all knowledge is situated in activity bound to social, cultural and physical contexts. The central idea in situated cognition is that learning is inherently social and shaped by interactions among people, the tools they use, the activity they engage in and their sociocultural environment (Hansman, 2001). Knowledge is seen as inseparable from the occasions and activities of which it is a product (Brown et al., 1989). In other words, cognition and context are inseparable entities (Boitshwarelo, 2011). Situated Cognition takes as its starting point the theory of social and ecological interaction and builds towards a more comprehensive theory by developing increasingly detailed analyses of information structures in the contents of people's interactions. The cognitive perspective on the other hand that takes the theory of individual cognition as its basis and builds towards a broader theory by incrementally developing analyses of additional components that are regarded as contexts (Greeno, 1997).

I agree with the situated cognition approach that knowledge is tightly bound to activities. It is clear to me that the operators' most significant work knowledge is acquired through their daily work and therefore bound to those activities. This is also one reason why it is important to study the operators while they are working; otherwise, it is difficult to access their work knowledge.

4.5.2 Distributed cognition

Distributed cognition is a branch of cognitive science that proposes that human knowledge and cognition are not confined to the individual. Instead, they are distributed by placing memories, facts or knowledge on the objects, individuals and tools in our environment. The operators and the material world are considered as part of the same cognitive system. The distributed cognition approach originated from Hutchins' (1995) ethnographic studies on-board navy ships. He argues that many foundational problems in cognitive science are consequences of researchers' ignorance of the nature of cognition in the wild. Most knowledge of cognition was learned in laboratory experiments, but little is known about the relationships of cognition in the captivity of the laboratory to cognition in other kinds of culturally constituted settings. I fully agree with Hutchins about the need to study cognition in the context in which this process actually occurs.

From our own studies of train drivers, it seems apparent that train drivers use physical objects in the world to carry their knowledge. For example, the train drivers often learn that, when they pass, for example, the large pointy tower, they need to start applying braking force in order to stop at the platform. Such knowledge is very important among skill drivers. However, I would not consider the large pointy tower to be part of any cognitive system.

I would rather consider the train driver to have a mental model that includes the large pointy tower as a marker for when to start braking. I definitely acknowledge the importance of the environment, but my starting point regarding cognition is rather that concepts, such as cognition and awareness, are not a property of humans and machines, but a property of humans only.

4.5.3 Naturalistic decision making

The naturalistic decision making (NDM) approach states 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 (Klein, 1989). In daily life most decisions are efficiently made in a naturalistic manner, typically in situations with a limited amount of time, inadequate background information, vague goals, changing conditions and a varying amount of experience. NDM originated from Klein's field studies of firefighters, intensive-care units and other emergency services. The approach focuses on cognitive aspects such as goals, plans, SA and decision making.

　　Within my own research, I have been greatly influenced by NDM, partly because of its attention to cognitive aspects such as decision making, goals and strategies. However, my strongest connection to NDM is the view that decisions need only be good enough for the situation at hand, rather than optimal in some absolute sense. I have seen in various work contexts, that the operators are not trying to make optimal decisions and I believe it is a very important thing to understand for system development teams. If there is a development project in progress at some company with the goal of developing a new work tool for some group of users, the team often has a strong tendency to expect that the users want to behave in an optimal manner. This incorrect assumption about human behaviour will lead the team to develop work tools that are poorly adapted to how the real work is performed by the users.

4.5.4 Cognitive systems engineering

The field of cognitive systems engineering (CSE) emerged from the work of Jens Rasmussen at the Danish National Laboratory at Risø (Rasmussen, 1968, 1982). In contrast to more mechanistic perspectives, CSE clearly acknowledges that cognitive aspects of the studied socio-technical system are needed. The term systems include both the technical system as a whole as well as the humans working with it (Hollnagel & Woods, 1983). Hollnagel and Woods (2005) summarise the goal of CSE in the following words: *"In a single term, the agenda of CSE is how can we design joint cognitive systems so they can effectively control the situations where they have to function"*. Woods and Roth (1988) describe CSE as being an ecological approach that puts emphasis on understanding human behaviour in complex worlds, as well as about changing the behaviour and performance in that world. The

CSE approach can be achieved by providing system designers with tools that facilitate the creation of work systems, where humans and technology have matching models of each other and where the system can stay in control in a dynamic context (Vicente, 1999). CSE methods have been developed to guide this process of discovery so that the specific challenges of a work domain can be captured and addressed throughout the design process. CSE contributions to design products and artefacts can aid the design team in developing solutions and making trade-offs that take into account the full complexity of the joint cognitive system (Militello et al., 2010).

5   Work analysis

Earlier in this thesis I addressed the complexity of the operators' work, as well as some specific issues, such as automation, SA and mental models that are particularly important. I have given examples of accidents related to these concepts. I have argued that it is necessary to acquire a deep under-standing of how the operators think and act in order to reduce the risk of accidents while at the same time increasing productivity and improving the operators' health. To reach this understanding of how the operators think and act, I have pointed towards ecological approaches, and specifically, the CWA framework. This chapter briefly describes a set of work analysis methods, starting with Taylor himself.

5.1   Task analysis

Task analysis is among the earliest approaches to work analysis. With its roots in the field of scientific management, Taylor (1911) performed task analysis using a stopwatch to time the performance of unskilled workers (Figure 16).

Figure 16: Observing the workers and measuring the duration of different work tasks.

The more psychological aspects of the operators' work task were first examined during the Hawthorne studies (Heizer & Render, 1999). While studying how lighting conditions affected the workers' performance, they unintentionally noticed that other variables had a larger impact on the workers' performance than lighting. Specifically, they concluded that the attention given to the workers during the study had a larger effect than the effect of different lighting.

When the field of HCI emerged, the scope and complexity of task analysis increased. Task analysis now includes a range of techniques aimed at obtaining descriptions of what people do, representing those descriptions, predicting difficulties and evaluating systems against functional requirements (Jordan, 1998). One early example of this is hierarchical task analysis (HTA) (Annett & Duncan, 1967). HTA is useful for decomposing complex tasks, but has a narrow view of the task. HTA breaks tasks into subtasks and operations or actions. These task components are then graphically represented using a structure chart. HTA entails identifying tasks, categorising the tasks, identifying the subtasks and checking the overall accuracy of the model (Crystal & Ellington, 2004). A significant limitation of HTA is that it treats the operator's cognitive processes as a black box (Shepherd, 2001). Within the field of HCI, it is well accepted that it is important to understand the structure of human cognition to support cognitive-intensive tasks.

5.2 Cognitive task analysis

Card et al. (1983) developed a more cognitive approach towards task analysis. The GOMS task analysis method models tasks in terms of a set of *goals*, a set of *operators*, a set of *methods* for achieving the goals, and a set of *selection rules* for choosing among competing methods for goals. GOMS analysis can be used to predict the quality of an existing system or prototype (Preece et al., 1994).

Close analysis of cognitive activity has led to another class of techniques known as cognitive task analysis (CTA) (Crystal & Ellington, 2004). The development of CTA is motivated by evidence that the studied *"tasks have become more intricate, knowledge-intensive, and subject to increasingly integrated forms of technological support, traditional forms of task decomposition appear to have an overly restricted scope"* (Barnard & May, 2000). CTA targets more abstract, high-level cognitive functions as compared with the GOMS (Militello & Hutton, 2000). It also requires deep engagement with a particular knowledge domain, working closely with subject-matter experts to elicit their knowledge about various tasks (Chipman et al., 2000). CTA represents an attempt to capture task expertise. Because expertise is often tacit or personal in nature, it can be much more difficult to analyse than the explicit actions considered by HTA. CTA requires *"making explicit the implicit knowledge and cognitive-processing requirements of jobs"* (Dubois & Shalin, 2000).

5.3 Cognitive work analysis

Within CWA, Rasmussen et al. (1994) and Vicente (1999) emphasise how knowledge about ecological vs. cognitive aspects should be treated in the work analysis process. Studying socio-technical systems, humans and machines imply certain constraints that have to be acknowledged and dealt with effectively. The CWA framework suggests that ecological constraints should be identified and considered before moving towards aspects that imply more cognitive constraints.

It is important to note that CWA is neither a theory nor a method; rather, it is a framework describing how to identify behaviour shaping constraints in the environment and in what order these constraints should be taken into account. This is referred to as a formative analysis in contrast to both descriptive and prescriptive methods of 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 17).
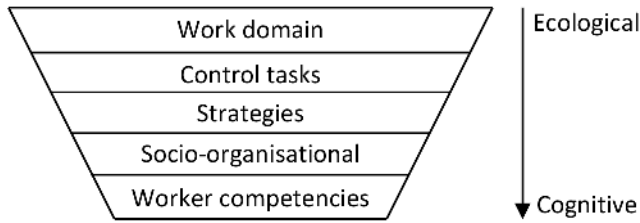
Figure 17: The five levels of analysis in the CWA framework (Vicente, 1999).

Vicente (1999) used the nuclear accident at the nuclear power plant at 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 an operator's mental models because the mental model can be incorrect. The fact that the operator's mental models can be misleading does not mean that they should be ignored. On the contrary, the CWA framework suggests detailed analysis of the operator's work. Instead of relying on verbal protocols as fact, CWA tries to use such data to identify constraints of the environment. Furthermore, this structured approach can also result in the identification of operator misconceptions.

I believe that such an ecological approach is necessary if we wish to achieve a design that accounts for events that were unanticipated by the system designers. The CWA framework provides valuable information about intrinsic constraints of the work under investigation, which is of great importance when approaching design.

6 Knowledge elicitation

The previous chapter discussed methods that can be used for work analysis. These work analysis methods either involve or depend on some form of knowledge elicitation. The scope of my own thesis work is primarily devoted to this knowledge elicitation task. This chapter briefly describes the history of knowledge elicitation, from early introspective approaches to modern verbalisation procedures used within HCI.

6.1 Sources of information

When analysing the work tasks of skilled operators within socio-technical systems, there are many methods available to extract the information about the operator's work. The work analysis could be based on information from many data sources:

- Documentation such as checklists, descriptions of work processes, etc.
- Statistics about different events, e.g. the number of deviations and frequency of user interaction in a certain phase
- Protocols from interviews with people in different work roles
- Data from questionnaires with people in different work roles
- Protocols from observational studies of the operators
- Verbal protocols from the operators' verbalisations

Most of these data sources require a good deal of researcher involvement to obtain the actual data source (e.g., to plan and execute an interview, or participate and document an observational study). Because the analysis tends to be qualitative in nature, it is important to note that the involvement required to obtain the information provides a significant amount of knowledge in itself. The involvement in the information acquisition process may sometimes be more valuable than the analysis of the resulting sources of information. It is of course also valuable to combine many sources of information to get a more versatile picture. Paper II, for instance, describes a study of train drivers in which several knowledge elicitation methods are combined; direct and indirect observation, structured interviews, concurrent verbalisations, and CV.

6.2 Tacit knowledge

Before going into detail about the pros and cons of the different methods of knowledge elicitation, it is necessary to consider a particular challenge when studying skilled operators. Polanyi (1974) points out that when we acquire skill, we also acquire a corresponding understanding that defies articulation. In other words, professional skills are often tacit, at least to some extent.

Ericsson and Simon (1980; 1984) state that subjects might have trouble verbalising information about highly automated processes, something often referred to as implicit, silent or tacit knowledge. It is particularly difficult to verbalise skill-based work, referring to the most automated level of the SRK taxonomy described by Rasmussen (1983).

The SRK taxonomy describes the skilled level of work as automatic, i.e. it is 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 rare situations but still known to happen. The knowledge level is the highest and most demanding level in which rules cannot be applied directly. Instead, some thinking and reasoning are first necessary. In contrast to Rasmussen, Hammond's (1995) cognitive continuum theory, derived from Brunswik, 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 plan, whereas the prehistoric hunter reacts simultaneously to stimuli (visual, audial, etc.) and makes non-retraceable instantaneous decisions.

Polanyi (1967) distinguishes between tacit and explicit knowledge. Tacit knowledge is described as being personal, thereby hard to formalise 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 explain how this recognition is performed. The implication here is that even if an operator really wanted to describe how they think and reason about their work, the human mind sets limitations to this process. Nonaka (1994) divides tacit knowledge into a cognitive element related to mental models and a technical element that refers to know-how, crafts and skills that apply to a specific context. 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 and computer software codes.

When discussing tacit knowledge with one of my colleagues at the department, I once used the term silent knowledge as a synonym of tacit knowledge, after which he quickly replied: *"Silent knowledge? But it is not silent; it rather bursts out if one is willing to see it"*. After some further dis-

cussions, I understood his point more clearly. There is so much information to uncover when studying skilled work. Although it might not be explicitly presented orally, or compiled into a set of well-defined facts on a paper, the knowledge of skilled operators is expressing itself through their actions and expressions at work. If one has an interest to determine what is under the surface, one will find much to learn, which is precisely what this thesis aims to achieve.

6.3 Methods for knowledge elicitation

Studying normative descriptions (such as checklists), descriptions of work processes often provide an unambiguous picture that can be easy to relate to when designing a new technical system. Unfortunately, they often fail to explain how the users actually work, but rather how management or former system developers want them to work. To get an understanding that better describes how the actual work is done, some form of interview or question-naire method can be used. One problem with asking skilled operators what, why or how they do their work is that many of their actions are highly auto-mated and therefore they are not aware as to how or why they do things in a certain way. They will generally not have any trouble providing answers to such questions, but they might unconsciously answer what they should be doing (e.g., according to an official work process description) rather than what they actually are doing. It becomes problematic when their honest ex-planations do not represent what they are actually doing.

One way to get closer to what they are actually doing is to observe the operators while they are working. Then it becomes the researchers' task to interpret why and how different tasks are executed, which differs from inter-views where the operators themselves perform part of this interpretation. However, it can be very difficult for researchers to interpret implicit details without any help from the operators. One common way to overcome this limitation is with some form of verbalisation. With the verbalisation method, the operators describe what they are doing and thinking while they are doing it, or they do so in retrospect (e.g., while looking at a video recording of their work).

6.4 History of verbalisation

6.4.1 Introspection

The journey towards understanding how people think dates at least back to the Greek philosophers. For example, Socrates (470 BC – 399 BC) urged the

people of Athens to develop their own understanding and thereby acquire knowledge that would lead to goodness and happiness. The following quotes of Socrates are found in the writings of his students (Figure 18):

"Knowing yourself is the beginning of all wisdom"

"I know that I am intelligent, because I know that I know nothing"

"The unexamined life is not worth living."

Figure 18: Mosaic found in an excavation in Rome, picturing a skeleton with Socrates quote: "Know thyself".

By examining his own thoughts, Aristotle concluded that thinking corresponds to a sequence of thoughts, with brief transition periods between these thoughts that were inaccessible (Ericsson, 2001). Aristotle's idea of thought sequences is still considered valid today (Ericsson & Crutcher, 1991).

It took more than 2000 years before the act of self-reflection was examined in a more objective and structured way. The modern field of psychology is said to have emerged with the establishment of the Wilhelm Wundt Institute for Experimental Psychology in Leipzig, Germany in 1879 (Figure 19). Wundt proposed that introspection could be used to study conscious mental states. According to Wundt, no one could observe an experience better than the person having the experience, and therefore introspection was a key

method in the study of psychology. The goal was to describe an experience without interpreting what was happening. Wundt did not invent the concept of introspection but his experimental control of its use was novel (Schultz, 1975). Wundt goal was to dissect the mind into its basic elements, and believed that by using introspection in his experiments, he would gather information about how a person's mind was working. However, the entire research field of introspection quickly disappeared after a controversy over the notion of *"imageless thought"*.

Figure 19: Wilhelm Wundt seated in front of his research team at the institute in Leipzig, Germany.

6.4.2   Behaviourism

The rejection of introspection opened the field of behaviourism. Behaviourists claimed that the method of introspection was unreliable, subjective and not measureable. Behaviourists focus on observable behaviour rather than consciousness (Wilson & Keil, 2001), (Schultz & Schultz, 2012). A subject's acts, thoughts and feelings should be regarded as behaviours, and any psychological disorders should be treated by altering behaviour patterns or modifying the environment (Skinner, 1984). Thus, all behaviour can be clarified without the need to reflect on psychological mental states. Behaviourists consider the human brain as an inaccessible black box, with stimulus as input and response to that stimulus as output (Figure 20).

Figure 20: The inaccessible human brain viewed as a black box by behaviourists.

6.4.3   Cognitive psychology

As a response to behaviourism, a cognitive revolution took place in about 1950. Pinker (2002) lists five key aspects that characterise the change.

- The mental world can be grounded in the physical world by the concepts of information, computation and feedback
- The mind cannot be a blank slate because blank slates don't do anything
- An infinite range of behaviour can be generated by finite combinatorial programmes in the mind
- Universal mental mechanisms can underlie superficial variation across cultures
- The mind is a complex system composed of many interacting parts

The field of Cognitive psychology is concerned with internal mental processes, such as how people perceive, remember, think, speak and solve problems (Feist & Rosenberg, 2010). However, cognitive psychology differs from previous psychological approaches because of its fundamental rejection of introspection (Schunk, 1991). Furthermore, the approach acknowledges the use of scientific methods and the existence of internal mental states (e.g., belief, desire, idea, knowledge and motivation).

Introspection was also criticised by Nisbett and Wilson (1977), who showed that their subjects described their own behaviour in a reconstructive and interpretative way, rather than by true introspection, or as Miller (1962) put it even earlier, *"It is the result of thinking, not the process of thinking that appears spontaneously in consciousness"*. Curiously, people seem to be unaware of their own unawareness, rarely answering, *"I don't know"* when asked to explain their decisions. People freely give reasons for their preferences, even when it is clear that these reasons are confabulations and not accurate reports. Why are people so unaware of their unawareness? One reason may be that we do have access to a good deal of information that is immediate, compelling and privileged. That we experience a rich mental life makes it hard to recognise that most of our mental processes are not directly observable (Wilson & Bar-Anan, 2008).

Based on the IP model, Newell and Simon (1972) developed protocol analysis as a systematic means of educating and analysing think-aloud statements made by a subject concurrently with solving a specific problem. As a response to Nisbett and Wilson's critique, Ericsson and Simon (1980; 1984) tested conditions when verbal protocols provide valid data. Ericsson and Simon also classified verbalisation procedures into three categories with respect to the time of verbalisation: think aloud, concurrent probing and retrospective probing. Ericsson and Simon primarily concentrated their work on non-retrospective verbalisation methods because they assumed that the

content of a subject's short-term memory is available to verbal reporting, and not subject to rationalisation. To ensure that the concurrent verbalisation procedure results in reliable data it must be executed properly. Therefore, Ericsson and Simon conducted controlled experiments in which their subjects performed predefined tasks in laboratory environments. At the same time as they achieved better control of the verbalisation task, they lost some of the relevance in their data because of the limits imposed by their rigorous control.

6.4.4 Concurrent verbalisation

Concurrent verbalisation uses short-term memory processes and therefore provides accurate representations of cognitions during task performance (Whyte et al., 2010) and elicits many details about decision making (Kuusela & Paul, 2000). However, Ericsson and Simon (1980; 1984) point out that if subjects have to articulate information that is not already available to them, their performance may slow down. Dickson et al. (2000) further state that the performance of subjects may be degraded when carrying out concurrent verbalisation in time-critical dynamic tasks. Another problem with concurrent verbalisation is that it can distract the subjects from their primary task (Bartl & Dörner, 1998). In my research I have studied professional users while they are doing their normal day-to-day work in their own work environment. Unfortunately, professional users tend to adopt rather automated processes in their work, such that they have difficulties expressing their actions in words (Polanyi, 1974). Altogether, this makes it problematic to perform concurrent verbalisations on such experienced users.

6.4.5 Retrospective verbalisation

Retrospective verbalisation, on the other hand, makes it easier for the subject to explain underlying actions and cognitive aspects of the work task (Whyte et al., 2010; Pew et al., 1981), but it also requires the use of long-term memory. This retrospective approach and its reliance on long-term memory reduce the ability to provide a verbal report that corresponds to the original processes (Gibbons, 1983). According to Ericsson and Simon (1984), thinking-aloud protocols involve a direct verbalisation of cognitive processes in terms of successive states of information currently attended to, whereas retrospective reports represent parts of a memory trace developed based on this cumulative information. Therefore, retrospective verbalisation allows the subjects to rationalise to a greater extent their own behaviour. An operator might give a perfectly good explanation of some action taken and might be completely confident about the truth of the verbalised information when it is in fact incorrect (van Someren et al., 1994). The problem is caused by the rationalisation that takes place when subjects retrieve information from long-term memory. Wright and Ayton (1987) argued that a weakness with retro-

spective protocols is that infrequent problems might not be encountered. Hollnagel et al. (1981) treat this critique by reasoning that the protocols may be regarded as performance fragments in the sense that they do not provide a coherent description of the performance, but rather the necessary building blocks or fragments for such a description. Furthermore, Duncker (1945) states that a protocol is relatively reliable only for what it positively contains, but not for what it omits. The retrospective reports also tend to be biased towards describing positive aspects (Swann et al., 1987).

Lately, video recordings have been used to support the retrospective verbalisation task. Kuipers and Kassirer, (1983) used a technique called aided recall in which they capture audio data, video data or both, of an expert engaged in problem solving. These data are later used to help the same expert verbalise his or her thoughts about particular stages of the problem-solving task. Nielsen and Christiansen, (2000) suggest a similar idea, capturing video recordings of think-aloud sessions and then using the events shown on video to guide an interview. Finally, Bainbridge (1979) concludes that verbal reports can be a poor reflection of the mental activities of the subject, but that careful use of the verbalisation techniques can provide useful data.

Given all the research discussed above about when verbal protocols can be used and when they should be avoided, one would suspect that there should not be any problems with verbalisations as long as one adheres to those rules. However, despite this, many practitioners still perform verbalisation procedures in ways that researchers consider as questionable. For example, sometimes HCI practitioners apply retrospective verbalisations in a rather interpretive fashion, possibly resulting in incorrect data. The reason that HCI practitioners still do this is that they feel that they get valuable results from these studies, and that the resulting information helps them to improve the design of future computer systems. The HCI practitioners simply trust their subjects' descriptions of their thoughts and actions.

7 Collegial verbalisation

The previous chapter presented different knowledge elicitation methods and their pros and cons during the process of studying professionals at work. This chapter presents the new CV method in detail. Based on the individual contributions of each of my research papers, this chapter describes the strengths and weaknesses of the CV method.

CV differs significantly from the verbalisation methods discussed above in that the person performing the task is not doing the verbalisation. To open the exciting field of letting other subjects perform verbalisations, I refer to Nisbett and Wilson's (1977) classical review paper. In their often-cited review of verbalisation methods they conclude that when subjects explain their own behaviour in retrospect, they do not have access to the correct thought processes from that event. Consequently, they will only give a correct statement about their behaviour if the more current thought processes happen to match the original thought processes. The authors close their review with a reflection that they do not really want to believe themselves: *It is frightening to believe that one has no more certain knowledge of the working of one's own mind than would an outsider with intimate knowledge of one's history and of the stimuli present at the time the cognitive process occurred".* This quote nicely explains what verbalisation by other subjects is all about. Namely, to let an outsider with intimate knowledge of an operator's history and of the stimuli present at the time the operator's cognitive process occurred verbalise the knowledge of the operator's own mind. It opens a possibility of having other people verbalising one's own actions. In situations and contexts where domain knowledge is shared between colleagues, they might also share actions and cognitive strategies. With that background, it is now time to present the seven research papers included in this thesis. Together they describe how my research has evolved over the years. All the papers, except the first one, relate specifically to the CV method.

7.1 Paper I

Augmented reality as a navigation aid for the manoeuvring of high-speed crafts

I started my research career by studying the task of ship navigation. In light of the recent accident of the high-speed ferry MS Sleipner in Norway (Statens forvaltningstjeneste, Informasjonsforvaltning, 2000) several Scandinavian research projects assessed how such accidents could be prevented. In the case of the Sleipner accident misinterpretations of radar information and electronic sea charts were considered a contributing factor.

The intention of my research was to find alternative ways of presenting sea charts and radar information to minimise the risk of misinterpretation. Proceeding on previous research by Olsson et al. (2002), I conducted experiments to evaluate a novel visualisation approach involving AR. AR 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 et al., 1995). The goal of using AR was to support the navigator's information retrieval task. This support was done by allowing the user to keep direct visual supervision of the out-the-window scene using AR. The information traditionally presented using ordinary instrumentation was thereby accessible without having to look down (e.g., to look at the radar screen). Several experienced high-speed ferry operators performed different navigation tasks in a simulator. In this study the traditional way of presenting information was compared with our AR approach. The experiments were set up in a traditional experimental psychology fashion, with hypotheses, dependent and independent variables. The study resulted in some quantitative data regarding the operator's visual focus and the ship's deviation from the route.

7.1.1 Results

Despite the results touching on relevant navigational aspects, I later concluded that the experiments did not represent enough of the complexity of the real HSC navigation task. In a real setting the operator has to integrate so much more complex information, as well as reach tough decisions in real time while many other long- and short-term tasks are happening simultaneously in which the operator might be more or less involved.

The more advanced ferry simulators available around the world today manage to create a much more realistic setting than the one used in my experiments and therefore such experiments become more meaningful and valuable. However, to capture the full complexity of the work there is still a need to study the work in its naturalistic setting.

In this paper the main concern was on the evaluation of the new visualisation approach. As indicated above, performing the evaluation in an experimental setting is problematic from a naturalistic standpoint. However, it is almost never feasible to evaluate new designs in a real work situation because of safety risks, unless the new design has gone through substantial simulated testing in advance.

In the remaining research papers of this thesis attention is shifted towards the analysis phase, where it is easier to study the real work setting. To be able to improve the operators' work situation it is crucial to obtain a good understanding of the actual work. My efforts in working with these ship navigation experiments helped me realise that discrepancies exist between experimental and real world settings. This, in turn, led me to study people in their real work settings.

7.1.2 Comments

The experimental set up of my first research project was unfortunately designed in a way that makes it possible that the results are a product of a learning effect. With the intent to examine the effect of using AR as an information source, the experimental conditions should have been designed to compensate for learning effects in relation to the use of AR. However, the experiment instead followed an order that compensated for the learning effect of the fog vs. darkness conditions. This is how the experiments were conducted:

Subject 1&3:
1. Control condition
2. Darkness
3. Darkness + AR
4. Fog
5. Fog + AR

Subject 2&4:
1. Control condition
2. Fog
3. Fog + AR
4. Darkness
5. Darkness + AR

Hence, the results of this paper suffer from a learning effect. However, within the context of this thesis, the results inspired me to focus on more ecological research approaches. For that purpose, this paper is still a valid source of inspiration.

7.2 Paper II

Bridging the gap between analysis and design: Improving existing driver interfaces with tools from the framework of cognitive work analysis

The initial ideas that eventually led to the development of the CV method occurred before I started working as a PhD student. Using a broad range of knowledge elicitation methods, the co-authors of Paper II performed detailed studies of train cab drivers. This work was first published in Jansson et al. (2005).

The background was that my co-authors wanted to find methods for assessing the train drivers' knowledge as a basis for the design of new driver interfaces in train cabs. They first tried concurrent verbalisations, but soon ran into problems because the train drivers were driving without thinking aloud. Despite the fact that they were hinted when not thinking aloud while driving, they very often became silent. It was later decided to use colleagues as informants. First, this seemed to be a good idea just because we would get an observer's opinion about each target driver's actions. Later, we realised that the colleagues should perform the verbalisations just as if they controlled the train themselves.

Video recording sessions were made of six professional train drivers while driving along four types of real-schedule routes (e.g., long-distance routes, commuter traffic routes, etc.) (Figure 21). Seven other professional train drivers individually performed CV while watching these video recordings.

Figure 21: The instrumentation and forward view of one of the studied train cabins.

7.2.1 Results

The data were analysed using Vicente's (1999) abstraction-decomposition space tool (AHDH) to identify behaviour-shaping constraints. The second study discussed in Paper II concerns a design task. Based on the intrinsic constraints identified in the knowledge elicitation phase, a team of train drivers and HCI experts performed several design sessions to find better ways of presenting train track information to the train cab drivers. The results from the knowledge elicitation phase of the CV method served as a valuable input to the design phase. This study resulted in a more complete understanding of the work tasks of train drivers. More specifically, the study helped to explain what kind of behaviour-shaping constraints the information environment imposes on the train drivers.

7.2.2 Comments

The second part of this paper consists of a study in which users were involved in the actual design of a new work tool. Specifically, six train drivers were involved in the design phase of a new train driver user interface. This bottom-up approach is similar to the participatory design (PD) technique, and hence does not follow the more top-down approach of CWA. One of my colleagues performed this study. Apart from the second part of Paper II, the remainder of my research follows an approach in line with the CWA framework, i.e. to gather information as input to design in a top-down manner.

It should be apparent by now that this thesis is grounded in CWA and not in the PD tradition. Nonetheless, approaches such as PD can complement more structured analytical top-down approaches. Furthermore, applying CWA in a highly iterative cycle of analysis, design and evaluation enables users to have a large impact on the design solutions being iterated, although without considering the users as being designers, but rather as informants in the iterative design process.

7.3 Paper III

Collegial verbalisation – A case study on a new method on information acquisition

Prompted by the positive results of using colleagues as informants, we decided to involve colleagues in our studies of high-speed ferry operators. In the previous study colleagues' involvement occurred ad hoc as a response to the inability of the train drivers to think aloud while driving. Now the collegial approach could be executed in a more planned and structured fashion; at the same time, we tried to formalise the method to allow for reuse as well as

scientific examination of the method. Hence, this is the first paper to describe the new CV method in detail. The paper also provides a comprehensive description of the problems with the traditional well-established verbalisation methods.

Given the opportunity to study a high-speed ferry crew running a vessel between the mainland of Sweden and the island of Gotland, we decided to videotape the actions of the bridge crew during a four-hour journey. Four video cameras were used to capture the crew, instrumentation and surroundings (Figure 22). Individually, four colleagues watched and commented on the actions and decisions made by the video recorded crew. These protocols were then compared to examine to what extent these four colleagues agreed on the observed behaviour.

Figure 22: The four video cameras used on the high-speed ferry. Upper left: forward view. Upper right: captain and first mate. Lower left: instrumentation. Lower right: monitor with electronic charts and RADAR.

7.3.1 Results

The comparative study led to some important conclusions. First, that the comparison between the colleagues' verbal protocols showed many examples of conformity, indicating that the participants agreed in these cases. The CV method introduced the possibility of having several statements about the same topic because multiple colleagues could be used as informants. This advantage made it possible to assess the conformity between the protocols by comparing the protocols to each other. High agreement between statements would indicate better conformity, and vice versa. Retrospective verbalisation cannot assess or increase its conformity in this way because nor-

mally the work of a single individual is studied. Therefore, only one person can perform the retrospective verbalisation and no comparison can be made.

A second conclusion was that the method could identify buggy mental models. When using concurrent and retrospective verbalisation procedures, the narrators will normally not be able to identify their own misconceptions or buggy mental models while they watch themselves on video. They consider themselves to act appropriately based on their own current knowledge. However, when colleagues watch the same video, they sometimes tend to make spontaneous reactions after perceiving that something is wrong, often followed by an explanation about how the person in the video is thinking and why this is erroneous.

It is worth mentioning that we do not claim to be able to determine who has a correct mental model in some normative manner. We only get indications that there is a conflict between the colleagues' and the operators' mental model. Hence, one of them might have an erroneous understanding of the system. Finding such misconceptions indicates that there might be a need to improve the observability of the system to aid operators to form a more coherent understanding of the socio-technical system.

7.3.2   Comments

The method chapter of Paper III refers to the need of using suitable methods before the protocols from the CV method can be used as input to design. However, the paper fails to address what kind of methods that would be. The road of going from analysis to the design phase might not be that straight forward and hence a short comment is in order.

First, verbal protocols do not specify design solutions, although some people involved in system development projects tend to want to go from problem to solution with little or no reflection about whether this is the only idea or whether it is a good idea. There are many ways to make better use of the protocols. One can select interesting aspects and generate design solutions and let users comment on these, or even test prototypes of the solutions. Vicente's (1999) CWA framework suggests a more top-down approach. It strives to identify intrinsic work constraints that need to be satisfied if a device is going to support work effectively. The protocols from the CV method are not limited to any particular form of approach, but are well-suited to support the analysis activities during all phases in the CWA framework. The in-depth analysis of socio-technical systems will benefit from the advantages of being able to identify buggy mental models and to assess conformity by comparing protocols.

Here follows another comment on Paper III. The first two hypotheses posed in the paper, refer to the ability of the CV method to give more detailed and reliable information than traditional retrospective verbalisation methods. During the work with the later research papers and discussions with psychology researchers, I came to realise that I had to revise my inter-

pretation of observable behaviour. When I developed the hypotheses and conclusions in Paper III, I included more types of behaviour into the observable category than the term suggests. Consider the following excerpts from three hypothetical verbal protocols:

1. *"The captain moves a joystick on the bridge."*
2. *"The captain now adjusts the joystick to reverse the ship in order to dock properly."*
3. *"The nodding between first mate and the captain in this case means that they both have understood that the approaching ship, which so far was only visible on radar but would soon appear behind an island, is positioned in such a way that they cannot proceed through the fairway using the auto pilot. The nod infers that the first mate, about 10 minutes later, has to disable the auto pilot and manually control the ship while passing the approaching ship and then return to the fairway and reactivate the autopilot"*

The first excerpt could be made by someone who has never visited a ship bridge, but has acquired some basic knowledge of what a captain and a joystick is. The second excerpt requires some knowledge about the properties of the particular joystick (e.g., a domain expert on ferries). The last excerpt requires detailed knowledge about the specific work tasks and routines onboard the particular ship. Such content can be made by someone who was part of that event, or possibly a close colleague. In contrast to the first excerpt, the last two excerpts include identification of non-observable behaviour. However, my previous perception of this material only considered the third excerpt as non-observable behaviour.

Hence, we have shifted terminology towards non-observable behaviour in the later research papers (Paper IV-VII).

7.4 Paper IV

Verbal reports and domain-specific knowledge: A comparison between collegial and retrospective verbalisation

The protocols from the four ferry operators only allowed us to compare in-between the colleagues. To gain a better understanding of the similarities and differences between CV and traditional verbalisation methods it was also necessary to compare the CV protocols with protocols from traditional methods. To accomplish this goal a more elaborate study was required.

We had the chance to set-up a comparative study in the challenging work environment of train dispatching (Figure 23). Such an environment also allowed us to evaluate the CV method in a somewhat different work domain. Previous studies concerned trains and high-speed ferries. These two work

vehicle domains share some important characteristics. In both domains the decisions made and the actions taken are based on direct perception and action on-board a vehicle (dynamic properties are evident and important in these situations). The train dispatchers' task to supervise and control train traffic involves decisions based more on analytical problem solving.

Figure 23: The workstation at the train traffic control centre.

The verbalisation methods could be used in this situation to study the effects of the introduction of a new software tool for planning and controlling train traffic in a region at a specific train traffic control centre. Four experienced train dispatchers participated, both as objects of study and as retrospective and collegial narrators. The CV protocols were systematically compared with retrospective protocols to achieve a better understanding of the similarities and differences between the two verbalisation methods. Our hypothesis was that collegial verbal protocols could provide protocol data close to the structure and content of verbal reports based on retrospective verbalisations.

This paper also describes two other methods that let other subjects perform the verbalisation: elicitation by critiquing (EBC) (Miller et al., 2006) and the concurrent observer narrative technique (CONT) (McIlroy & Stanton, 2011). The approach and the intention of these additional methods are roughly similar, but they have been developed individually to meet the unique needs of each research team.

The first method, EBC, involves letting experts critique the actions of students or practitioners. Miller et al. used video recording and note-taking to capture the actions of a student performing an analysis task related to a rocket launch failure. The student was asked to think aloud while performing the task. This phase of the study was later followed by showing screenshots and transcripts of the students' actions to a domain expert, providing cues for

the experts to guide a discussion about what the expert considers correct or incorrect actions and what they would have done themselves in the same situation. The critiquing phase was repeated for six experts individually. Thus, multiple experts provided information about the same topic.

The second elicitation method, CONT, involves letting an expert (the practitioner) perform a task in a simulator while another expert (the narrator, whose level of experience is close to that of the practitioner) views the actions and narrates concurrently. The narrator is placed so that he or she can see the practitioner's actions and at the same time verbalise these actions without the practitioner overhearing. This set up gives the narrator a detailed realistic picture of the practitioner's actions.

In comparison, our own CV method involves videotaping practitioners while they perform their work tasks in their normal work setting. This phase is later followed by having a colleague of the practitioner watch the video recordings and verbalise the actions of the practitioner. Multiple colleagues can repeat the verbalisation phase individually in order to get several protocols. The narrating colleague's interpretation can be more or less accurate. However, keep in mind that the colleague has experience from the same work tasks in the same work environment and that it concerns work tasks repeated routinely by both the practitioners and the narrating colleagues.

7.4.1 Results

We concluded that the CV method produced verbal protocols close to the retrospective verbal protocols when considering the protocols as a whole, as well as the topics addressed (referred to as the protocol and topic levels). However, when looking more closely at the detailed statements there were very little similarities (referred to as the statement level). We also concluded that the collegial protocols could be used as a complementary source of data. It seems possible for a colleague to report verbally on the practitioners' observable behaviour in the same way as when the practitioners are doing a retrospective verbalisation, and that it may be possible for a colleague to explain some of the non-observable behaviour of the practitioners.

In addition to an assessment of the CV method, the train dispatcher study also resulted in comprehensive results regarding the strengths and weaknesses of the new train traffic software tool. These results appear in Isaksson-Lutteman et al. (2009).

7.4.2 Comments

In the method chapter of Paper IV it is stated that four subjects are enough to perform the intended protocol comparisons. The set up of Paper II and III is used to support this claim.

To elaborate a bit further on this claim, it can be added that the comparative protocol analysis in previous papers often showed many similarities

among three to four of the protocols, which would indicate conformity. In terms of gathering more data, adding even more subjects should still contribute, but not for our comparative purpose. This claim is supported by Nielsen and Landauer (1993) who argue in a somewhat different context that the majority of the usability problems are observed by using no more than five subjects. Furthermore, the practical consideration of adding more subjects becomes considerable when performing video recordings, transcriptions and comparisons of protocols.

The method chapter also contains a statement noting that we avoid a potential recency-effect by having a few weeks between the video-recording phase and the verbalisation phase. This procedure will have a negative effect on the retrospective verbalisation task, but not on the CV task and therefore produces an unfair comparison. It is an advantage compared to let the retrospective verbalisation take place immediately after the video recording. However, it is just as relevant to compare CV with an immediate as a delayed retrospective verbalisation. In our study it was not feasible to perform an immediate comparison because of the time needed to analyse the video recordings, identify relevant sections for analysis, define probing points and synchronise the playback of the multiple video sources. The real value of the comparison between CV and delayed retrospective verbalisation is that it shows the difference between someone that has been part of the studied events and colleagues who have not experienced the events themselves. Regardless how long time that has passed after the event, there is a difference between someone that has experienced the events and someone who has not. The model described in Figure 24 (see chapter 7.5.1 below) elaborates further on the difference between immediate- and schemata-based retrospective verbalisation.

7.5   Paper V

Collegial verbalisation: The value of verbal reports from colleagues as subjects
Throughout the development of the CV method, we have struggled to find ways of assessing it properly. Paper III compared in-between the colleagues' protocols while Paper IV compared collegial protocols to protocols using the more established retrospective verbalisation method. In this paper a set of key principles are presented and the method is assessed towards these principles. To give an overview of precisely how the method evolved over time the paper summarises the results from the three previous studies involving the CV method (the studies described in papers II, III and IV).

7.5.1 Results

Here follows the proposed set of key principles that can be used to evaluate any verbalisation method:

1. *Suitability of subjects' verbalisations as scientific data*
2. *Process of extracting data from behaviour*
3. *Separation between data and theory*
4. *Theoretical presuppositions*
5. *Process of inferring thought processes from behaviour*

The key principles are mainly based on the seminal work of Ericsson and Simon (1980, 1984). The paper ends with a discussion about how the CV method meets these principles.

A new model for distinguishing between different verbalisation methods is also suggested to assess the methods' degree of familiarity with the studied tasks (Figure 24).
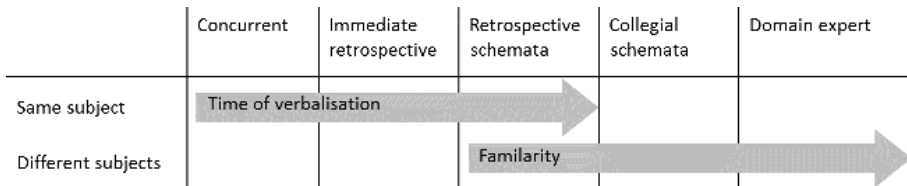

Figure 24: Verbal probing procedures in relation to time and familiarity.

7.6 Paper VI

Collegial collaboration for safety: Assessing situation awareness by exploring cognitive strategies

In the previous papers the incentive for developing and using the CV method has primarily been to improve the knowledge elicitation phase when studying skilled professionals. Here, the incentive shifts to encouraging a group of professionals to share and learn from each other's cognitive strategies. By having close colleagues sharing cognitive strategies, we expect the team to develop proactive thinking as a means to avoid non-safe interactions with technical equipment and suboptimal working procedures because of organisational demands. The purpose is to evaluate whether this knowledge elicitation procedure can be used as a basis for exploring how colleagues can learn from each other. The paper presents the design of a more applied study that the authors plan to carry out and some preliminary results from a pre-study.

We will study an ICU at a Swedish hospital. Hence, the study will evaluates the use of the CV method in this new work domain.

7.6.1 Results

This paper expands the use of the CV method to a learning tool for the colleagues themselves, rather than just knowledge elicitation for an external analyst or designer. It gives the organisations/teams/companies an opportunity to identify and learn from the differences in acting and thinking among the members in the team and between the teams. However, this paper primarily explains the set up of a planned future study and therefore no results are presented.

7.7 Paper VII

Recognizing complexity – A prerequisite for skilled intuitive judgments and dynamic decisions

In this paper we look at the operators' decision-making tasks to evaluate and assess what kind of decision strategies they employ in their respective work contexts. We propose that intuitive judgments and decisions are best understood if the evaluation is based on an assessment of the strategies employed by individuals during the decision-making process.

This paper describes how experts make immediate judgments and how they take measures for action based on continuous evaluation of the ongoing decision-making process. We use the CV method to elaborate on the non-observable behaviours from the practitioners' judgments and decisions. Specifically we make comparisons between the studied work domains (train drivers, ferry operators and train dispatchers) to find differences and similarities relating to the operators' temporal and spatial perspective of their work, as well as their ranking of work-related goals.

7.7.1 Results

Combining the results from train-driving, high-speed ferry operation and train dispatching, we found similar patterns in terms of the operators' temporal and spatial perspective of their work, as well as their ranking of work-related goals. The results are based on the actual decision-making tasks (e.g., when a train operator starts to brake when approaching a platform). Concerning the temporal perspective, train drivers and high-speed ferry operators exhibited similar types of time interval.

1. *Long-term planning*
2. *Short-term interval*
3. *Immediate sense interval*

The paper also discusses a fourth time interval consisting of past events that the operators use in making judgments.

Concerning the spatial perspective, we also identified some shared aspects. Professional vehicle drivers tend to think and behave in particular ways during different parts of the journey. A few rough categories of sub-parts of a journey were identified:

1. D*eparture (a train leaving a station or a ship leaving port)*
2. *On route (a train on the line at cruising speed or a ship running by auto pilot)*
3. *Confined areas (a train passing through an area with speed restrictions or a ship navigating through an archipelago)*
4. *Arrival (a train braking to stop at a platform or a ship running its bow thrusters to moor)*

Regarding ranking goals, we found that all operators consider safety first, but that there are always practical matters that continuously cause conflicts between safety and other goals, such as following a timetable, maintaining passenger comfort or minimising fuel consumption.

The paper concludes with a few examples of good and bad design solutions, and how the pros and cons of these designs are related to their ability to support the operators' need of temporal and spatial information and control in the decision-making tasks.

8 Discussion

While the previous chapter presented the results of my research papers, this chapter discusses how the papers relate to the research questions presented in Chapter 1.4. Below, follows a recapitulation and discussion of my research questions.

1. A theoretical assumption that the usage context largely shapes the users' actions and therefore makes an ecological approach possible.

With the intention to improve the work situation for operators in socio-technical systems, it is important to acquire a good understanding of how the operators' act and reason in their work. Throughout this thesis, I have discussed the difficulties of learning about the operators' work if it is not studied under natural field conditions. I have also raised several difficulties when studying professional users in the field: (1) understanding implicit events resulting from automated actions, (2) the problems of rationalisation that increase when having to retrieve from long-term memory and (3) the problems of distracting the operators with a secondary task (i.e. a verbalisation task).

All of these challenges in studying professionals fuelled our desire to explore different approaches to knowledge elicitation during the insight phase (Paper II). In combination with the limitations identified during our experimental approach (Paper I), it resulted in my basic assumption, namely that an ecological approach was appropriate for our ambition to understand the work tasks of professionals in socio-technical systems.

2. Can the CV-method overcome some of the problems related to traditional knowledge elicitation methods?

Based on the insights from paper I and II, my research motivated me to formulate the collegial approach into a proper method. The idea to use colleagues as informants was rooted in my strong ecological perspective, in general, and the belief that socio-technical systems shape the operators to think and act in a similar fashion and hence develop shared knowledge, in particular.

Papers III, IV and V, concerning method development, together define the CV method in detail and identify its properties. For each of my research

projects, I became increasingly encouraged to continue to develop the non-intrusive verbalisation method.

Altogether, my research papers include descriptions of the following:
- How the method evolved
- How to apply the method
- A theoretical review of similar knowledge elicitation methods
- A new model distinguishing between different verbalisation methods based on their degree of familiarity with the studied tasks
- Key principles needed to assess knowledge elicitation methods
- Detailed assessment of the CV method when compared with traditional knowledge elicitation methods
- Examples of application in several types of work domain

Because of the careful formulation of the new method, it could be repeatedly applied and properly assessed. My methodological approach was necessary to be able to identify all the exciting advantages (and weaknesses) of the CV method.

3. *What is the empirical contribution of the CV method?*

My research papers have shown the following qualities of the CV method:
- Produces several verbal protocols from the same event
- Results in protocols that can be used as an additional source of data
- Produce verbal protocols close to the retrospective verbal protocols in both quantity and content
- Can report on a practitioner's observable behaviour in the same way as when a practitioner is performing a retrospective verbalisation
- May be able to report on some of the non-observable behaviour of the practitioner
- Can assess the conformity between the collegial verbal protocols
- Can acquire more information as compared with the retrospective verbal protocols
- Can identify misconceptions or buggy mental models

Overall, the method makes it possible to acquire deeper knowledge of the operators' work tasks and can hence act as a strong complement to other knowledge elicitation methods.

8.1 Critique to collegial verbalisation

8.1.1 The HCI approach to verbalisations are interpretive

Most of the psychology researchers that I have referred to in this thesis regarding verbal protocols (e.g., Nisbett & Wilson, 1977, Ericsson & Simon, 1980; 1984) attempt to ascertain whether the verbal protocols are representative of the original actions and thoughts they are meant to describe. Within our research in particular, and usability research in general, the verbalisations are usually allowed to be more interpretive as a means to get information that is more meaningful.

Hughes and Parkes (2003) divide verbalisations into three types: First, when simple vocalisation is possible without further processes because the information is reproduced directly (e.g., Pennington et al., 1995); second, there may be a need to describe or recode information into a verbal form (for instance, if the original format is graphical) (e.g. Narayanan et al., 1995). Third, verbalisations that may require further processing, such as when a researcher prompts the participant for an explanation or interpretation (e.g., van der Veer, 1993; Chi et al., 1989). To once more allude to the title of Nisbett and Wilson's (1977) article the third and most intrusive type of verbalisation may force the participants to *"tell more than they can know"*.

Usability researchers often use the third type of visualisation (Boren & Ramey, 2000), either to access more details about something or simply to direct the narrators to verbalise about matters the researcher considers more relevant. A large difference exists between the first and third types of verbalisation and thus the resulting protocols will have different qualities.

The first type of visualisation can result in data that are closer to the actual thoughts of the subject, but to achieve such data experimental psychologists commonly let students perform predefined tasks in a simulated environment. Such direct vocalisation tasks result in data based on what is in the subjects' short-term memory.

As discussed throughout this thesis, we are studying the automated behaviour of professional operators. These operators are not able to report on their implicit actions by simple vocalisation. Hence, verbalisation methods that require further processing, such as retrospective verbalisation with prompting for explanations, are needed. In practice, the HCI community gains valuable information by performing interpretive retrospective verbalisations.

However, I believe that the HCI approach to verbalisation often unintentionally (or intentionally) encourages subjects to be too interpretive. This prompting can be problematic. However, it is less of a problem when the intention of the verbalisation is to identify information to serve as input to a design process, rather than as an exact representation of the original thought-processes. For an example of a situation in need of an exact representation of the original thought-process, consider a witness testimony in a court trial.

Furthermore, most HCI approaches are highly iterative, thereby continuously verifying the information that was used as input. Ideas and concepts can be iteratively tested by using prototypes to ascertain that the interpretation of the information was valid.

8.1.2 The CV method is too interpretive

This issue of verbalisations being too interpretive is particularly relevant regarding the CV method because the use of colleagues will increase the level of interpretation even further than a traditional HCI approach to retrospective verbalisation. However, for gathering data as input to design, I believe that the increased level of interpretation is acceptable if the method at the same time provides a way of ascertaining conformity between protocols.

As discussed earlier, the CV method distinguishes itself from modern verbal reporting techniques in that multiple protocols are produced and compared with each other. Recall also that the narrators are professionals with extensive experience of the same environment, situations and tasks of the practitioners. Thus, it is plausible that their interpretations are similar to those of the practitioners being studied.

Ericsson and Crutcher (1991) point out that the traditional verbalisation techniques have been put on a secure scientific foundation by careful analysis of the different types of reports and conditions under which valid reports may be elicited. By doing so, these techniques stand out as trustworthy as compared with introspection. Based on this thinking, one can argue that the CV method needs to establish the same level of assessment as traditional verbalisation techniques to determine when valid reports may be elicited.

The CV method needs further assessment to determine when valid reports may be elicited. The CV method results in more interpretive reports than retrospective verbalisation. However, I do not think the CV method suffers from the same methodological problems as introspection. To understand why we first need to clarify what the major problems with introspection are. Here follows Ericsson and Crutcher's (1991) description of the three major issues with introspection:

(1) It is questionable whether subjects can give detailed descriptions of thoughts. The nature of thinking is too dynamic to make such descriptions possible.

It is only the results of thinking that we consider useful data, not how the subjects are thinking.

(2) It is questionable whether the reported characteristics are valid in introspection. Subjects' reports have a privileged status inconsistent with traditional science based on reliable inter-subjective observations.

The CV method does not give the subjects' reports any privileged status. On the contrary, the CV method allows for a unique comparison between several verbalising subjects.

(3) It is questionable whether the act of introspection can be performed without changing the process of thinking. Efforts to uncover specific information about a thought transform the mental state corresponding to that thought.

The CV method has not been developed to define the original thought process from the studied event, but rather to elicit valuable information for redesigning the work task/tools of the work context. Furthermore, we do not encourage or teach the colleagues to analyse or report their thought processes. Only the results of thinking are regarded as data. While people using the introspection approach often extensively trained their subjects to report specific types of information, the CV method tries to determine what types of information naive subjects can reliably report when given simple verbalisation instructions. However, it should be added that the CV method distinguishes itself from both introspection and the more modern verbal reporting techniques because of the multiple protocols that are produced and compared.

8.1.3 The colleagues' reports are simply expert commentaries

In this thesis I have compared CV with more traditional verbalisation methods. This comparison has been relevant in assessing the CV method. However, it may not be relevant to regard CV as a method comparable to traditional verbalisation methods, largely because the primary condition of having the subjects verbalising their own thoughts is not met. It could be argued that our colleagues simply provide expert commentaries and that this per se has nothing to do with concurrent or retrospective verbalisation. Is there something about using colleagues in the CV method that makes the CV protocols better than an expert commentary?

The results of the CV method differ from both retrospective verbalisation and expert commentaries (Figure 24). It is true that the colleagues have never experienced the specific events being studied and therefore interpret the practitioner's actions based on their own knowledge and experience from similar events. However, they can recognise and utilise similar situations from their long-term memory and verbalise based on these retrieved memories of past situations. The CV method is therefore sensitive to how closely the colleague's knowledge and experiences resemble those of the practitioner.

Concerning retrospective verbalisation, the practitioners can utilise their long-term memory to recall what actually happened when performing the verbalisation. However, as Nisbett and Wilson (1977) feared and as already

been pointed out in this thesis several times, *"one has no more certain knowledge of the working of one's own mind than would an outsider with intimate knowledge of one's history and of the stimuli present at the time the cognitive process occurred"*.

Regarding the domain experts, we consider them knowledgeable about the work domain and the general work tasks, but without any experience from the work tasks in the specific work context being studied. If they have such specific knowledge, we would consider them colleagues in the sense that they would be suited for the role as colleagues in the CV method. Hence, without these experiences, the domain experts cannot recognise and utilise similar situations from their long-term memory. Accordingly, we cannot acquire the important task-related implicit information that we are looking for from the domain experts. It would perhaps be worthy to run a comparative study between colleagues and domain experts to determine whether such differences really exist.

9 Future work

The primary purpose of this thesis has been to understand the operators' work with the intention of later being able to design useful work environments for these and other operators. As has already been discussed in this thesis, user involvement in the knowledge elicitation phase is of utmost importance. In the broader context of an entire system development project a user-centred system design approach should cover all necessary phases of a project iteratively. It would therefore be of great benefit to evaluate the usage of the CV method throughout an entire applied system development project to determine how it can contribute in different phases of the project cycle.

It would also be highly valuable to run the CV method in an applied system development project to determine how efficient the method can be executed when applied in practice. In this thesis the CV method was applied in a very structured manner to perform different scientific comparisons at the same time. If the purpose were only to apply the method to acquire knowledge without assessing the method at the same time, the application of the method could have been be done in an efficient and less time-consuming way. This more practical approach would preferably be executed by someone who has not taken part in the development of the method and who is not a member of the research team, so that they could apply it in their own manner and discover their own benefits.

Other utilities of the CV method are possible that do not involve redesigning the work environment. First, the method could be used simply to identify misconceptions (buggy mental models) among operators. Letting a group of operators study each other's work tasks using the CV method could reveal such problems as misconception and lack of knowledge. From a safety perspective, it is essential to identify such buggy mental models. Earlier in this thesis I described how an operator's incomplete/incorrect mental model contributed to the accident at the nuclear power plant at TMI. Although the operator's mental model had served him well for many years, the specific situation just prior to the accident revealed serious deficiencies of his mental model (Vicente, 1999). More broadly, the method could be used as an educational tool to improve the operators' cognitive strategies, e.g. by letting colleagues learn from each other by studying each other's actions. This kind of interactive learning and collaboration among operators could improve efficiency, safety and provide a better work situation for the operators by reduc-

ing their mental workload. We have already discussed this approach in Paper VI, but we have not yet presented any results from such a collaborative learning study. The CV method could possibly also be improved by incorporating other methods within completely different research fields, such as team learning.

So far, the method has been applied to study train drivers, high-speed ferry drivers, train traffic dispatchers and medical staff at ICUs. It would be worthy to determine how much knowledge is being shared among professional colleagues in other work domains (e.g., administrative office work).

In the scientific community researchers in the field of decision making could also use the method as a tool to identify and compare different cognitive strategies used by their subjects. Based on observable behaviour, it is difficult to understand how professionals think during decision-making tasks. It is my belief that the CV method can reveal some of the non-observable behaviour of professionals.

Finally, before concluding I want to encourage others in the scientific community to proceed on the research path to explore how to study and learn from professionals at work.

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Thanks!

Summary in Swedish

Jag har i min forskning studerat förare av höghastighetsfartyg och tåg, samt trafikledare på tågledningscentraler, med avsikten att se om det går att förbättra deras arbete. Det kan t.ex. handla om att ge dem tillgång till rätt information vid rätt tillfälle så att de kan ta kloka beslut och därigenom också minska risken för trafikolyckor. Förutom säkerhetsaspekter så kan man också hitta sätt att förbättra arbetsmiljön samt effektivisera arbetet. Om man arbetar med att t.ex. styra ett fartyg eller tåg, så formas man som förare till att utföra arbetet inom vissa givna ramar. Det handlar delvis om vilka tekniska förutsättningarna som finns (t.ex. fordonet manöverförmåga eller vilken information som finns tillgänglig om fordonet eller trafiksituationen), delvis på hur omgivningen ser ut (t.ex. omgivande trafik, väderförhållanden) och det beror även på vilka krav som omgivningen/organisationen ställer på föraren (t.ex. att upprätthålla säkerheten, följa tidtabellen, minska energiförbrukningen).

För att kunna förbättra situationen för dessa förare, så krävs det först att man skapar sig en djup förståelse för hur deras arbete går till, vilka strategier de använder i sitt arbete, vilken information som är kritisk, vilka arbetsrelaterade mål föraren anser är viktiga, vad som är roligt, svårt, jobbigt eller farligt, m.m. När man har byggt upp kunskap om detta kan man sedan använda denna kunskap för att hitta potentiella förbättringar i arbetet. Min forskning har fokuserat på att skapa denna djupa förståelse för förarnas arbete.

Det visar sig dock av många skäl vara svårt att studera deras arbete. Här följer ett exempel, från mina studier av arbetet ombord på bryggan på ett höghastighetsfartyg, som illustrerar en av svårigheterna;

Som observatör ombord på bryggan noterade jag en gång hur kaptenen skapade ögonkontakt med sin förste styrman och sedan nickade lite diskret, varpå styrman nickade tillbaka. Eftersom jag inte förstod vad det betydde, så frågade jag kaptenen efter att de nått slutdestinationen på resan. Han förklarade då att nickandet betydde att både han och styrman hade förstått att det fartyg som än så länge bara syntes på radarn, var positionerat på ett sådant sätt att de inte skulle kunna fortsätta köra med auto-piloten. Nickningen innebar därför också att styrman efter cirka 10 minuter skulle behöva inaktivera auto-piloten, manuellt styra fartyget under mötet och sedan återaktivera auto-piloten.

Personligen blev jag väldigt överaskad och imponerad av att en så subtil gest kunde förmedla vad en kollega skulle ägna sig åt under den efterföljande halvtimmen. Av denna historia kan man konstatera två saker som är viktiga för min avhandling:

1. Att kollegorna på fartyget har en god gemensam bild av hur deras arbete ska genomföras, eftersom det räcker med så subtil kommunikation för att kommunicera

2. Att det är väldigt svårt för en utomstående observatör att förstå hur arbetet går till, eftersom deras rutinmässiga arbete ibland inte kräver någon explicit kommunikation

Min forskning har med detta som en utgångspunkt undersökt om hur man kan utnyttja kollegornas gemensamma kunskap för att överbrygga de svårigheter som uppstår när man studerar t.ex. fordonsförare. I samband med mina fältstudier har jag utvecklat en metod som heter Kollegial Verbalisering. Metoden går ut på att man videofilmar arbetet t.ex. på en båtbrygga under en resa och sedan låter man kollegor som inte varit med på resan titta på videofilmerna och kommentera vad som händer.

Det visar sig, spännande nog, att dessa kollegor tillsammans kan ge tillgång till ny information som inte är tillgänglig om man låter personen på filmen kommentera själv. En viktig skillnad som uppstår tack vare kollegorna, är att man kan få flera personer att beskriva samma sak. Detta kan då ge mer kunskap om det studerade arbetet, genom att varje kollega bidrar med en del ny information. Dessutom får man en hel del gemensam information från flera olika kollegor, vilket möjliggör att man kan bedöma samstämmigheten kring den gemensamma informationen. Ju högre samstämmighet det råder mellan protokollen, desto högre trovärdighet i dessa utsagor.

En annan intressant aspekt som mina jämförande studier avslöjat, är att metoden kan identifiera när någon av operatörerna har en felaktig mental bild av hur systemet fungerar eller hur arbetet går till. När operatören själv berättar om sitt eget arbete på videofilmen så tenderar man att återge en trovärdig berättelse, baserat på sitt långtidsminne. Man rationaliserar alltså omedvetet ev. oklarheter så att det framstår för en själv och alla åhörare som en rimlig berättelse.

Men när man istället låter en kollega återge händelseförloppet på videofilmen så visar det sig att de ibland spontant reagerar väldigt överaskade över operatörens beteende på filmen. Här följer ett fiktivt exempel som beskriver hur reaktionen brukar se ut; *'' Nej men vänta! Så kan han inte göra, inser han inte att det innebär att växeln kommer slå om för tidigt? Han inser nog inte att systemet inte längre är i grundläget''*. Vi har även funnit exempel på att kollegorna kan identifiera och beskriva implicita händelser som inte är direkt observerbara i filmen. Citaten ovan om kaptenen som nickar till förste styrman är ett exempel på en implicit händelse.

Sammanfattningsvis kan alltså den nya metoden Kollegial Verbalisering komplettera andra metoder för att studera personer som arbetar professionellt, och därmed kunna ge bättre input vid design av nya datoriserade arbetsverktyg, samt även sprida kunskap om arbetsstrategier kollegor emellan. Långsiktigt kan metoden därför också leda till förbättringar av säkerheten, arbetsmiljön samt hur effektivt arbetet genomförs.

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