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Knowledge elicitation as abstraction of purposive behaviour

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Abstract

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Researchers use knowledge elicitation methods to document expert knowledge for the primary purpose of understanding cognitive processes and with this understanding, technical solutions to resolve human factors issues can be produced. This dissertation offers a novel perspective on knowledge elicitation as an abstraction process. Such a theoretical framework has emerged by consolidating the ecological approach of Brunswikian psychology with the ideas of tacit and personal knowledge of Polanyian epistemology. Traditionally, knowledge elicitation has been considered an extraction process in which knowledge can be readily transferred from one individual to another. Here, this traditional position is rejected in favour of Polanyi's premise that much of the knowledge individuals possess is tacit in nature, which implies that it cannot be documented easily, expressed in explicit form or explained. In this dissertation, knowledge is characterised as a personal process of knowing, highlighting context as a subjective knowledge structure of personal experiences that is formulated implicitly and indirectly over time through a dynamic interaction with the environment. Therefore, tacit knowledge cannot be articulated or shared; however, learners can be inspired by observing other individuals' purposive (i.e., goal-directed) behaviours and thus shape their own tacit knowledge once they practise the observed skills and develop conceptual understanding through reasoning about the learning process. Knowledge elicitation thereby makes use of observations, questions, or more structured process tracing methods in environments familiar to the observed individuals to elicit purposive behaviour from them. Accordingly, functional descriptions can be produced in this process that further conceptual understanding of a particular domain. Knowledge elicitation procedures are a powerful set of methods for reaching such functional descriptions. Moreover, by understanding the resulting knowledge elicitation data as an abstraction derived from multiple collection points in the same environment, the focus shifts from purely subjective mental constructs to the impact of environmental constraints.

Keywords: knowledge elicitation, expertise, context, human factors

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List of papers

The present dissertation is based on the following works by the author, which are referred to by their Roman numerals throughout.

I **Eliciting strategies in revolutionary design: Exploring the hypothesis of predefined strategy categories**
Löscher, I., Axelsson, A., Vännström, J., & Jansson, A. *Theoretical Issues in Ergonomics Science, 19*, pp. 101–117. 2018.

Author contribution: The work of this paper was initiated by Ida Löscher and the present author participated in planning and executing the workshops. Most of the paper was written in a joint collaboration between Ida Löscher and the present author. The present author focused mainly on the introductory, background, and discussion parts in writing the paper.

II **Collegial verbalisation — the value of an independent observer: an ecological approach**
Jansson, A., Erlandsson, M., & Axelsson, A. *Theoretical Issues in Ergonomics Science, 16*, pp. 474–494. 2015.

Author contribution: This paper was already a manuscript by the time the present author was asked to contribute. It had been returned by the journal with major revisions twice. The present author completely reworked the paper by inventing the term 'conspective verbal protocol', develop the memory model behind the method, drawing illustrations, and rearranging the narrative with a greater focus on theoretical underpinnings of the method.

III **On the importance of mental time frames: A case for the need of empirical methods to investigate adaptive expertise**
Axelsson, A. & Jansson, A. A. *Journal of Applied Research in Memory and Cognition, 7*, pp. 51–59. 2018.

Author contribution: This paper is a reworked conference contribution that was invited for publication in a special section on Naturalistic Decision Making (NDM). The conference paper was presented by the present author at the NDM conference in Bath, 2017. The paper was partly based on field studies carried out by the present author within the Assessment of Changes in Train Traffic Controllers Decision Making (UFTB) project. Concerning the writing, the present author focused mainly on the introduction, theoretical aspects on Collegial Verbalisation, and the general discussion. The extension of adaptive expertise was jointly written by the two authors.

IV **Experience and Visual Expertise: A First Look at Eye Behaviour in Train Traffic Control**
Axelsson, A. Under review.

<u>Author contribution</u>: The study reported in this paper, inspired by field studies, was planned by the present author. All data for the experiment were collected on-site by the present author. Statistical analyses were discussed and performed in collaboration with the author's co-supervisor, Mats Lind. The manuscript was written by the present author without editing contributions.

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Preface

Through the process of evolution by natural selection, nature has shaped life to resonate with the structures and laws of reality. Thanks to the characteristics of the evolved brain, organisms are able to move around and purposively affect reality. Now, the mind, with the body serving as a tool, can rearrange objects in the environment to work towards particular goals. Recently, the human mind has created technical and digital environments in which modern society takes its shape. Human Factors and other systems design-related fields deal with this restructuring of the environment through the development of systems for increased efficiency, effectiveness, and safety. What separates the Human Factors perspective from other perspectives is its focus on the human operator. The field is a reaction to more technology-centred design in which the human is often seen as an obstacle and where operators need to adjust to the system rather than developers tailoring the system to human capabilities. Technology-focused design projects are commonplace, often driven by economic interests given that investigations into user knowledge, abilities, needs, and wants can be tedious and costly. However, to design tools for the purpose of aiding operators to assist them in making informed decisions and achieving the intended goals efficaciously and safely, a human-centred perspective is needed. In this process, *knowledge elicitation* is a vital research tool in bridging knowledge gaps between designers and users.

As a researcher within Human Factors, a general understanding of psychological and cognitive aspects in professional behaviour is required. But, more importantly, the researcher must understand how proficiency manifests itself in the particular domain of interest. Expertise is highly task-dependent and professionals have domain-specific knowledge and skills developed through extensive practice within particular environments. Because the overarching goal of Human Factors is to minimise fatal errors in complex technical systems, it is crucial to have a firm grasp of the particular domain in which the system resides and to identify crucial aspects for developing and maintaining skills for informed decisions so that the developed systems can support these skills. Apart from the fact that this domain knowledge is necessary to develop a sociotechnical system, it can also provide more general insights into cognitive aspects of expertise. This latter aspect of knowledge elicitation is a central theme in the present dissertation.

Scientific research in Human Factors is generally either domain-specific (e.g., studying nuclear plant operators or aeroplane pilots) or subject-specific (e.g., studying situation awareness or sensemaking). This dissertation, however, is somewhat more general in character. The dissertation does focus on Human Factors, as the results reported have been obtained in Human Factors-related research. However, it should be underscored that methods of knowledge elicitation are also applicable to fields outside the scope of Human Factors. The aim of this dissertation is to bring forth a theoretical account of knowledge elicitation. The noun *elicitation* in the term will refer to the evocation of knowledge-based behaviour in studied participants that can be described functionally by an observer, rather than being referred to as a transfer of knowledge from the participant to the observer. In this sense, knowledge elicitation is considered an *abstraction* process rather than one of extraction. This view centres on the idea of tacit knowledge that is personal and situated in practice. In this view, knowledge, during interaction with the environment, is seen as a dual and dynamic act of learning and recalling rather than a collection of static memories.

For the present dissertation, four scientific works are appended that serve as the basis of this work. They all relate to the use of various knowledge elicitation methods in technology-related domains with professional users as the study participants. The dissertation summary is somewhat unconventional in that it aims to provide a synthesis of the four works, joining them together in a theoretical view of how professionals reach proficiency and how aspects of their developed knowledge can be functionally described with the help of elicitation methods. It will be argued that there is a need for environmental cues in elicitation processes to trigger this personal knowledge. Two influential frameworks will be used and interconnected to support this view. The first framework stems from the psychology of Egon Brunswik and the inter-relationship between the organism and its environment. The second framework is derived from the epistemology of Michael Polanyi as founded in his philosophical ideas of personal and tacit knowledge.

Contents

Part I:
Introduction

Human factor and contribution

Human Factors has its roots in the field of aviation, particularly the United States Air Force. The field developed in the wake of the world wars when researchers started applying psychology to study human decision making in safety-critical systems. In the early days of air warfare, training was deficient and the army simply relied on their allegedly well-engineered aircrafts. Anyone so inclined could become a pilot, and skilled flying aces gained high status among colleagues and the general public (Lewis, 1932/2009). Reports on fighter crashes between the two great wars revealed that a mere 2 % of crashes were due to actions of the enemy and 8 % were due to technical failures (Hobbs, 2004). Thus, it was concluded that an astounding per cent of aircraft crashes was due to pilot error. Thus, the term *human factor* was born, which refers to any property of the human agent affecting the performance of a technological system. After the great wars, inquiries into human errors were initiated to understand how it was possible that pilots would crash 'well-designed' aircrafts. In an early study, Fitts and Jones (1947) identified 460 pilot errors. These results would be used to design instructional material to educate and train future pilots, as well as to develop cockpit designs better suited for human mental and physical abilities. The Human Factors field was a reaction to the technological imperative that tends to drive the development of new systems and tools. The improvements to the field of aviation serves a clear indication that the 90 % of crashes initially blamed on pilot error alone were in fact a result of poorly designed sociotechnical systems. The resulting efforts to understand the complexity of human-system interaction helped to pave the way for the emergence of this new field pairing of engineering and psychology.

Human Factors is thus an applied, multidisciplinary science concerned with overall system performance by studying human behaviour within a particular system (ISO, 2004). The goal is to gain understanding of the strengths and limits of human mental and physical abilities, with the aim to create a smooth interaction between a technical system and its user. Human Factors is a combination of engineering, psychology, cognitive science, and physiology. From an engineering perspective, the field looks at interface design and anthropometrics to determine how to design tools; however, it also examines workplace design to ensure a safe and efficient work environment. From a physiology perspective, the field explores how medicines or the biomechanical make-up of humans affect performance in the sociotechnical system. From a psychology perspective, the field investigates learning, teamwork, and mental health within professional domains to understand how to produce instructional material and how to tailor the social environment. Finally, from a cognitive science perspective, the field looks at situated decision making and problem solving as well as the limits of mental and perceptual abilities.

The study of humans using technological artefacts is not unique to Human Factors but are today studied under a plethora of other guises: Human-Computer (-Machine, -System, -Robot) Interaction, Engineering Psychology, Cognitive Ergonomics, Interaction Design, User-Interface Design, Human-Systems Integration are a few examples of the fields studying human interaction with technology. What these fields all have in common is that researchers from each discipline study human behaviour to further knowledge on how to build artefacts better suited to the physiology and psychology of the users. The three main differences between these fields are whether the focus lies on (1) theory or application, (2) above or below the neck, and (3) professional or consumer products (Wickens, Hollands, Banbury, & Parasuraman, 2015).

As a researcher in Human Factors, it is impossible to grasp all the disciplines that compose the field. It is quite common to have a background in one of the constituent fields, gaining peripheral knowledge of other aspects in working or researching the field. The present dissertation should be categorised within cognitive science and psychology and it particularly concerns the theory behind methods for eliciting expert knowledge. Thus, the research is of a theoretical nature, focused on what goes on above the neck, and intends to provide a theoretical foundation for elicitation methods that aims to ultimately improve professional and educational tools. A first step in this direction was taken by Erlandsson (2014). Finally, Human Factors grew out of work on professional users, who have been the target population of study in the appended works.

Emphasising the human contribution

The Human-Computer Interaction and Human Factors tradition at the Information Technology Department of Uppsala University has always had human interest at heart. Rather than focusing on humans as error-prone components in otherwise fail-safe systems, the concern is to view the human as an asset and the focus is on the human value rather than human error. The research within the division spans across different domains but has always centred around the user perspective. The research focuses on how to achieve healthy workplace environments, user-involved deployment of new systems, tools for ethical decision making and critical thinking, inclusive design for functional variation, use of artificial intelligence for educational and social purposes, and methods to design for user autonomy and empowerment. This research focus is consistent with the trend in Human Factors of looking beyond the errors of humans (e.g., Reason, 2008; Woods, Dekker, Cook, Johannesen, & Sarter, 2010). Currently, society faces difficult challenges as automation is becoming an enduringly present component in systems development. High levels of automation and artificial intelligence will drastically change work environments and it is of utmost importance that these implementations are made with the human user in mind. In areas where cooperation between artificial and human intelligence is on the rise, Human Factors research will continually be important to develop reliable systems that act resiliently to ensure quality and safety. To revolutionise a domain with systems of a future world, professional knowledge and expertise of today have to be understood and preserved.

Eliciting the human contribution

To unlock domain-specific knowledge within a sociotechnical system, the use of elicitation methods is key within Human Factors. The information gained from these methods can improve systems in aspects for which support for informed decisions and actions are lacking. In addition, it can be useful in building intelligent systems in which responsibilities can be shifted to artificial intelligence where human cognitive capacities reach their limits. However, functionally translating knowledge of a domain into technical solutions is demanding and difficult, if not impossible, if the right methods are not used to evoke the relevant domain knowledge. Professional users are highly familiar with their domain and the current system, but they rarely have the technical expertise to understand how current systemic problems can be solved technically. And conversely, developers with technical expertise do not possess deep knowledge of the domain for which they are designing the system. Within systems development, this problem is seen as a designer-user gap. A fruitful approach to bridge this gap involves finding elicitation methods that can identify and describe purposive behaviour (i.e., purpose or goal-directed behaviour) of professionals in the current domain to inform designers. But, more importantly, abstracting the knowledge of professionals serves a more general purpose of furthering our understanding of cognitive behaviours in expert decision making and problem solving.

Aim and research questions

Humans are highly context-dependent organisms and development of knowledge structures arises through situated practice in a joint venture with the environment. Humans are not born as blank slates with respect to cognitive functionality, but neither are humans born with knowledge structures in place: there is high variability between each individual in skill and understanding, leaving humans with different abilities and capabilities as adults. At the root of the human contribution lies the ability to adapt to different surroundings and humans are highly sensitive to cultural influences. These are aspects that need to be considered to understand human cognitive processes more generally and are crucial to consider when working with elicitation methods. Therefore, the following research questions are explored in this dissertation:

RQ1 How can variability and adaptivity in human reasoning be accounted for and how is it affected by context?
RQ2 What is the environment's role in the development of knowledge?
RQ3 How can knowledge elicitation processes aid in Human Factors research?

Dissertation summary outline

After this brief and general introduction to the field of Human Factors, a description is provided of the domains in which the projects of the included works have been carried out: long-haul driving and train traffic control. The works are also be summarised for the reader. Knowledge is then discussed in relation to the theoretical works of Brunswik and Polanyi. Thereafter, a chapter on empirical findings of the development of proficiency follows to introduce the reader to characteristics of expertise. This information is given because professionals and domain experts have been the target population of study in the appended works. The following chapter turns to a discussion on methods to elicit professional purposive behaviour and examples of such methods utilised in the appended works are presented. Finally, the dissertation summary concludes with a discussion on the contribution of the included works relative to the research questions and the theoretical and empirical discourse on knowledge, proficiency, and elicitation.

Domains, research projects, and included works

The works included in the dissertation are reported studies conducted within one of three projects in which the present author has been involved. The research covers two distinct domains: (1) long-haul driving and (2) train traffic control. Short descriptions of these projects as well as descriptions of the domains in which they were conducted are provided to serve as a broader context for the reader. The works that make up the basis for the present dissertation are summarised under their respective projects to give the reader a review of the research as a foundation for the succeeding chapters. The works are referenced by their Roman numerals in the dissertation summary and their contribution to the development of the theoretical view outlined in the present dissertation is discussed in more depth in Part III.

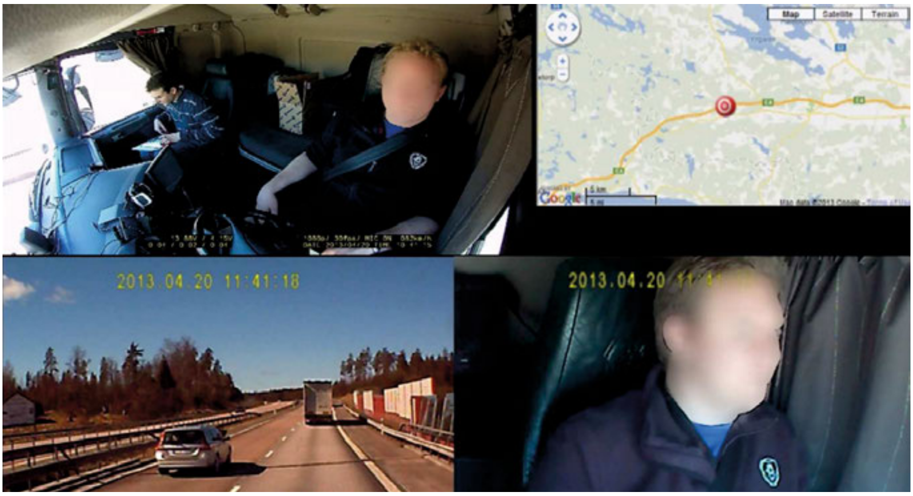


Figure 1. A modern heavy goods vehicle cab environment

The long-haul driving domain

Scania CV AB is a heavy goods vehicle manufacturer operating in Södertälje, Sweden. Apart from manufacturing, they also employ a number of drivers that perform long-haul cargo deliveries in Europe. Having drivers in-house entails having access to actual users to test newly designed vehicles. Driving heavy vehicles long distances is a challenging and demanding task as it often involves spending several days on the road in the vehicle's cab (Figure 1). Drivers are often overworked, fatigued, and feel the pressure of delivering on time. To become a skilled driver, familiarity with the roads travelled is required to permit rapid adaptation to changing traffic scenarios. In case of traffic congestion due to road work or accidents, the driver must be able to reassess the route to travel to the final destination to make deliveries on time. In addition, a driver must have good driving skills to optimise fuel use to meet demands on green driving and fuel costs. Taking breaks and allowing for adequate rest to stay vigilant and safe are crucial. All these factors mean that the driver must be skilled at making quick decisions, possess planning and orientation abilities, have a well-developed spatial perception, and a quick reaction capacity.

The auto industry today is navigating towards self-driving vehicles and Scania is no exception to this trend. With self-driving vehicles, the role of the driver will change dramatically, either by transitioning into a more supervisory role or by becoming obsolete altogether. One reason to still have drivers in the vehicle is for legal purposes to ensure someone is monitoring the vehicle; another would be that someone will still have to be responsible for loading and unloading cargo; and a third could be for safety purposes in the event of automation failure. Consequently, the driver would be relieved of

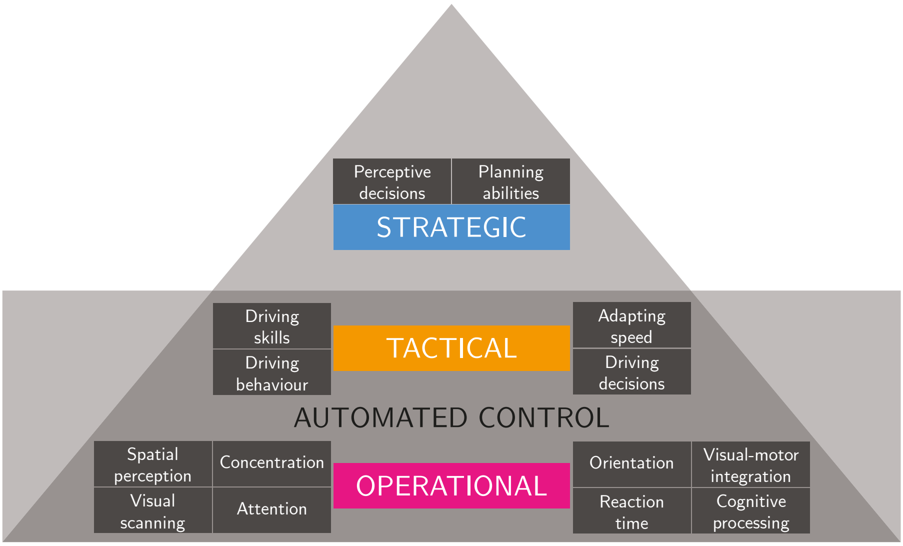


Figure 2. Illustration of the shift in heavy vehicle control when automation is introduced. Source: redrawn from Krupenia et al. (2014)

most tactical and operational duties but would still be in charge of strategic decisions and planning (see Figure 2). One possibility would be that drivers could be involved in administrative duties whilst on the road, which would mean that the vehicle becomes a travelling office with less need for logistics administrators in centralised offices.

MODAS

The Methods for Designing Future Autonomous Systems project (MODAS) was a collaboration between Scania CV AB, Interactive Institute Swedish ICT, Uppsala University, and Luleå University of Technology. The project had four goals: (1) create a method for design of future systems, (2) develop a driver environment for supervision and control of a highly automated commercial heavy goods vehicle, (3) develop assessment methods for the auditory display component of the driver environment, and (4) develop assessment methods for secondary task performance in highly automated commercial vehicles. Researchers from the Technology in Human Reasoning (TiHR) group at Uppsala University, of which the present author is a member, were mostly involved in driver knowledge elicitation and analyses of the work domain to serve as input for design. They were also in charge of usability assessments of the finished design of the driver environment. Paper I was a result of this project.

Paper I: Eliciting strategies in revolutionary design: Exploring the hypothesis of predefined strategy categories

When developing systems in completely new domains or domains that are being affected by revolutionary changes, target environments are unknown territory. In working with developing a human-machine interface for an automated long-haul heavy goods vehicle (Krupenia et al., 2014), several problems surfaced when trying to understand possible strategies that a future driver might use to manage everyday working tasks. To discover possible work strategies, the work domain must be understood. However, when it comes to future systems that revolutionise the work domain, such as the case with high-level automation, the precise impact the new system has on the work domain is difficult to anticipate. In these circumstances, researchers are at risk of being caught up in a 'catch 22', where the work domain is needed to develop a product, but to understand the impact the product has on the work domain, the product itself must exist in some form.

Throughout the project, the Cognitive Work Analysis framework, a widely used approach in the analysis of sociotechnical systems (Vicente, 1999), was employed. The current work domain of cargo delivery was modelled in the initial stages of the framework. However, once reaching the *Strategies Analysis* phase, difficulties were encountered when attempting to understand problem-solving strategies used in work tasks that were identified in the previous phases of the Cognitive Work Analysis framework. The idea of the Strategies Analysis is to elicit as many strategies as possible for performing a certain task to reduce risks of the future system placing constraints on the operators and ensure system resilience in case of incidents.

The problem encountered was that the future system is supposed to be a highly automated, self-driving vehicle. This means that, even though there is little difference in the overall tasks that the entire sociotechnical system is intended to perform in the future compared with today, responsibility to fulfil these tasks is shifting drastically when high automation is introduced. Thus, the operators' work will consist of more monitoring and less driving. To further complicate the analysis, handover and takeover of driving and other tasks should be flexible so that the operator can assume control in case of an emergency.

The paper presents how the analysis was carried out by adopting the formative strategies analysis from Hassall and Sanderson (2014). This method is a means to envision work strategies by using domain-independent categories based mainly on theories of human cognition. The authors provide strategy categories identified through an extensive literature review of works related to human cognition. The authors' categories were (1) intuitive, (2) analytical reasoning, (3) compliance, (4) option-based, (5) imitation, (6) avoidance, (7) cue-based, and (8) arbitrary choice. These categories are then meant to be populated with as many strategies as possible for tasks discovered through previous activities in the Cognitive Work Analysis framework. Once these strategies are defined, the researcher seeks to identify factors that may affect these strategies as well as factors that prompt each strategy.

In the MODAS project, strategies were identified through workshops with a total of 15 long-haul drivers using the 8 strategy categories provided by Hassall and Sanderson. The workshops were conducted in three separate sessions together with 4 to 6 drivers in front of a whiteboard. Driving scenarios familiar to the drivers were projected on the whiteboard and interface ideas of the future system were drawn directly on the projected scenarios. Modifications to the interface were contemplated whilst strategies of carrying out various tasks with a highly automated heavy goods vehicle were discussed. Current strategies to achieve work tasks were discussed and possible future strategies jointly elaborated upon. The study highlighted which tasks would be highly different in the future that puts high demands on interface design. It also underlined which tasks were to remain fairly stable, indicating that the same strategies should be possible to perform also in a future system.

The train traffic control domain

The Swedish railway system is controlled from 8 traffic control centres distributed across the country. In these centres, train traffic controllers communicate with train drivers, operators, maintenance contractors, and other controllers to coordinate the flow of traffic (see Figure 3). The job entails, amongst other tasks, surveillance of the traffic, creation of train routes through operation sites, shunting of trains, and applying safety routines during maintenance work. To become a train traffic controller, the person will have to pass rigorous perceptual, psychological, cognitive, and health tests. In addition, the person will have to spend roughly 10 to 12 months in training consisting of 10 weeks of theoretical lectures off-site with practical hands-on training interspersed on-site. Hands-on training is often performed by observing a more experienced controller and then being allowed to perform traffic control under strict supervision. Simulators have been introduced in a few control centres, which has cut down on training by approximately 2 months.

The control of train traffic is a dynamic decision task in which current decisions and actions impact future decisions. Dispatching trains is a complex and intricate problem-solving task that can put a strain on cognitive resources. Train traffic controllers thus need to employ proactive strategies that make use of time-table gaps to optimise track use and free up resources for unanticipated events (Roth, Malsch, & Multer, 2001).

To become a skilled and independent train traffic controller, you need to have at least 2 years of work experience. According to several train traffic control instructors (personal communication), what is characteristic of novice train traffic controllers is that they have a tunnel vision approach to controlling the trains; that is, they have a narrow focus on the current traffic situ-

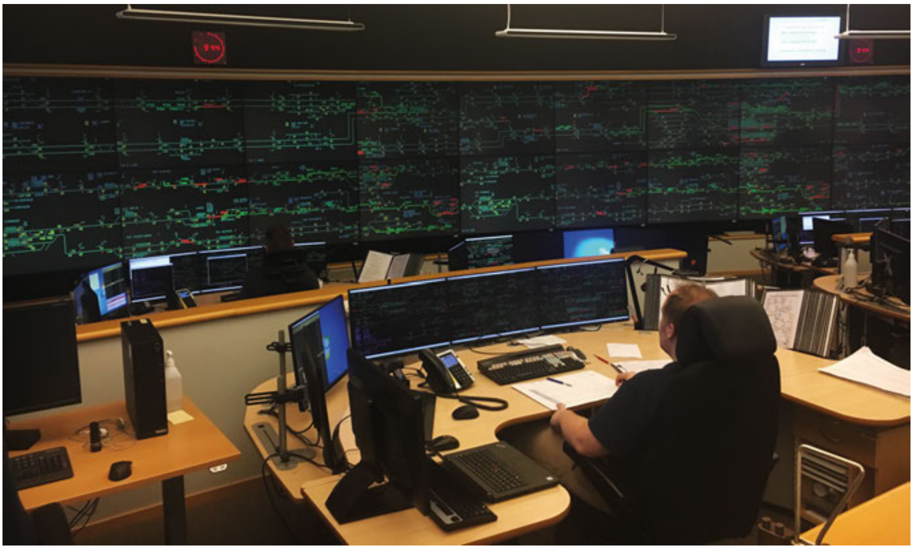


Figure 3. Work station in a train traffic control centre

ation, thereby having difficulties understanding the impact current decisions will have on future traffic situations. More experienced controllers work proactively, thinking ahead about upcoming complications and thus work within a larger time frame.

UFTB

As with most domains, train traffic control is heading towards higher levels of automation. Indeed, efforts at finding algorithms for capacity optimisation of the Swedish rail system have been initiated. The push for algorithms emanates from hopes of replacing human judgements and decisions with artificial intelligence. This process is incredibly challenging and will entail a transition period in which human and machine intelligence will have to work in conjunction to solve problems. However, it is not yet clear how the interface between operators and these algorithms should be designed because of the vast differences in the underlying processes of human and machine intelligence. Therefore, the Assessment of Changes in Train Traffic Controllers Decision Making project was initiated (in Swedish: Utvärdering av förändringar i trafikledarnas beslutsfattande; UFTB) and financed by the Swedish Transport Administration. The project aimed to investigate what forms of new research is necessary to bridge these differences. Approaches used in this project were observational studies of train traffic control and laboratory experiments with a micro world where students were performing a train traffic execution task. Paper II was a result of this project as well as a conference contribution to the 13th International Conference on Naturalistic Decision Making (Jansson

& Axelsson, 2017), which was presented in Bath by the present author. This conference paper was then invited for publication in a special section of the Journal of Applied Research in Memory and Cognition on naturalistic decision making. The paper was reworked to centre on adaptive expertise and is included in the present dissertation as Paper III.

Paper II: Collegial verbalisation — the value of an independent observer: an ecological approach

Verbalisation protocols are one of the most common approaches to acquire information from users within Human Factors and related fields. In these methods, users are asked to verbalise their behaviour so the researcher can gain a better understanding of the users' reasoning processes when interacting with technical systems. The information gained through these methods is valuable in understanding user needs and system flaws. There are generally two major types of verbalisation protocol: (1) concurrent verbalisation and (2) retrospective verbalisation. These protocols have some limitations. The former can impede on the working task and the latter is vulnerable to hindsight wisdom on the part of the verbaliser.

The paper offers a way to handle these limitations by making use of verbalisers other than the user that performed the task. This method can only be performed in environments where verbalisers are well familiar with the task domain. The method has been developed by the TiHR research group over the years in its work on knowledge elicitation in professional domains. The current author coined the term *conspective verbalisation* to distinguish this protocol from the other protocols. The protocol has been used in conjunction with either a concurrent or retrospective protocol to form a compound method called *Collegial Verbalisation*. A main feature of the method is that it uses colleagues who share a work environment and who have done so for many years. Of importance is that the verbalisers are well familiar with the workplace environment because it will then trigger knowledge that have been shaped by experiences in the environment. This familiarity qualifies the colleagues to comment on each other's knowledge and behaviour because they possess similar skills and understanding of work task performance by being exposed to nearly equivalent environments. When verbalisers observe their colleagues performing at the workplace, knowledge gained from experience of being in similar situations are triggered and they are therefore able to express what is going on in the minds of their colleagues. These verbal reports can then be compared with verbalisation reports of the target operator and together these data serves a more objective view of the work tasks than any of the constituent verbalisation techniques do alone.

Paper III: On the importance of mental time frames: A case for the need of empirical methods to investigate adaptive expertise

For a long time, research on expertise primarily focused on well-defined and rather stable domains such as chess playing or physical sports. The research tended to focus on understanding the development of refined routine behaviour and popularised the idea of 10 000 practise hours to achieve expert level performance (Ericsson, Krampe, & Tesch-Römer, 1993). However, as research ventured into more dynamic domains, it was acknowledged that there is another aspect to the concept of expertise that relates to handling changes in the environment. In such a domain, vigilance and creativeness are fundamental characteristics for successful adaptation to changes. For example, firefighting, aviation, or traffic control professionals often deal with novel situations and need to be able to handle such situations appropriately. This form of expertise has been called *adaptive expertise*. Recently, Hutton et al. (2017) performed a literature review on the subject in an effort to formulate a definition of the term. Their proposed definition was, "Timely changes in understanding, plans, goals, and methods in response to either an altered situation or updated assessment about the ability to meet new demands, that permit successful efforts to achieve intent" (p. 83). Furthermore, they highlighted three key elements of adaptiveness: (1) understanding of a situation, (2) actions required to achieve intent, and (3) self-awareness to balance the situational and task demands with the ability of the individual (and the resources at his or her disposal) to achieve the intent.

In Paper III, the definition by Hutton et al. (2017) was acknowledged but an elaboration on the key elements was proposed as the authors in Paper III believed that some important aspects were missing. Instead of referring to understanding, the authors in Paper III made use of the term 'recognition', which is more in line with the field of Naturalistic Decision Making of which adaptive expertise is a central construct. Within this decision paradigm, it has long been recognised that professionals in dynamic environments employ recognition-primed decision making rather than reasoning about options. In Paper III, it was also suggested that action to achieve intent and recognition of situational cues are two alternating cognitive processes running continuously until natural closure is reached. For self-awareness, a more operational and useful aspect of self-awareness was outlined, namely self-monitoring. It was suggested that self-monitoring balances action and recognition processes in that adaptive experts must be aware of their own limits to avoid critical situations from developing and subsequently escalating into an unmanageable situation. An amendment to the key elements was also made in acknowledging mental time frames. Through empirical data, it was demonstrated that experts in dynamic environments must consider time and thus develop cognitive strategies leading to proactive behaviour. An adaptive expert must be sufficiently experienced to understand within what time frames actions need to be taken to stay in control of the situation. It was thus concluded that adaptive expertise hinges on cognitive strategies of handling the demands of action and recognition processes, self-monitoring, and finding strategies to cope under time pressure. Finally, the authors in Paper III argued that the notion of adaptive expertise should be empirically explored and Collegial Verbalisation was seen as a viable and suitable method for further inquiry.

UFTB II

This project was a continuation of the UFTB project that aimed to investigate development of expertise in train traffic control. The project explored potential use of eye tracking equipment in studies of train traffic control. The project resulted in a study planned, designed, and conducted by the present author in Paper IV.

Paper IV: Experience and Visual Expertise: A First Look at Eye Behaviour in Train Traffic Control

Paper IV presents a novel study of visual expertise in train traffic control. Studies on visual expertise tend to make use of static stimuli in controlled environments to distinguish novice from expert eye behaviour. Dynamic stimuli are rarely used and so far no paper has been published in which these behaviours have been studied in a naturalistic setting. The study was performed in a train traffic control environment with simulated train traffic data. The tasks of the study were those that train traffic controllers face in their everyday work. The tasks were performed during a 30-minute train traffic scenario designed in collaboration with on-site instructors. As a theoretical base, metrics of a meta study conducted by Gegenfurtner, Lehtinen, and Säljö (2011) were used to investigate whether the same eye behaviour patterns found in the meta study would also occur in a more naturalistic setting.

The study showed support for the previously established relationship between years of experience and eye behaviour. Accordingly, train traffic controllers with more years of experience were faster at fixating on areas relevant to the task. Moreover, they produced more fixations and spent more time looking at relevant areas. In contrast to previous studies, saccade lengths were shorter for the more experienced train traffic controllers. This result is not surprising considering the task environment. Controllers use paper graphs to determine the planned position of a given train, and less experienced controllers will shift their gaze between the paper graph and screen much more often than experienced controllers, which causes their overall saccade lengths to be longer.

A noteworthy result was that two other measures of expertise did not correlate as expected with the eye tracking metrics. A ranking was made by two independent instructors that work closely with the participants and a measure of the participants' proactivity was calculated. The mean rank of the two instructors was used in a correlation analysis with the eye tracking metrics. The analysis showed a largely diametrical result to that of years of experience. The proactivity measure only displayed a correlation with saccade length, which was negative, as was the case with years of experience. It was therefore argued that visual expertise is not necessarily correlated with expert performance, but rather with years of experience of being trained in a particular environment.

A novel view on knowledge elicitation

The appended works summarised above contribute to furthering our understanding of expert behaviour as well as the development of elicitation methods for design and research purposes. In exploring the outlined research questions, the remainder of the present dissertation is a synthesis of these works. The argument for a novel view of knowledge elicitation as methods to evoke purposive behaviour in professional users to describe knowledge functionally through an abstraction process will be presented. The first step towards this goal is understanding the nature of knowledge and how it develops.

Part II: Background

Knowledge-based behaviour

Immanuel Kant, the famous 18th century German philosopher, argued that human knowledge is limited in its scope. This notion is based on his dichotomy of phenomenal and noumenal reality (Kant, 1781/1922). The distinction is founded in the sensual and non-sensual duality of objects (see Figure 4). In perceiving an object, the organism does not experience it as it truly exists; instead, it is filtered through the organism's limited senses, only able to capture certain wavelengths or frequencies, for example. When looking at an object, what forms the image of the object is a scatter of photons reflected upon the object, some of them hitting the retinas of the eyes. This process implies that it is not actually the object itself that is seen, but only its reflection. Kant thus drew the distinction between the thing-in-itself (das Ding an sich), or *noumenon*, and the experience of it, the *phenomenon*. Through perceptions, organisms only experience the phenomena of objects and not the intelligible objects, that is, not the noumena.

Brunswikian psychology — Purposive behaviour

Egon Brunswik (1903–1955) is not a generally recognised name, but some of his ideas have made a strong impact on methods in psychology, especially those on ecological validity and representative design have outlived him, even if few researchers actually know their originator. In fact, most often these ideas have been misunderstood and misrepresented (Hammond, 1998). However, his legacy is being preserved within Human Factors-related research owing to the appreciation of ecological aspects in the applied psychology of human-technology interaction (e.g., Bennett & Flach, 2011; Brehmer, 1996; Flach, Tanabe, Monta, Vicente, & Rasmussen, 1998; Kirlik, 2006). What makes Brunswik unique is his ecological perspective in which he considers the environment an equally important aspect in psychology as the organism under study. He proposes that the structure of the environment must be studied as much as the structure of the organism if we hope to fully understand behaviour (Tolman & Brunswik, 1935). This type of systematic investigation of the environment to understand behaviour has been central in the theoretical development of the Collegial Verbalisation method outlined in Paper II and III. This is a psychology founded in Darwinian evolution with which psychological functions are selected for across generations of organism-environment interaction. Brunswik's approach to psychology has been termed *probabilistic*

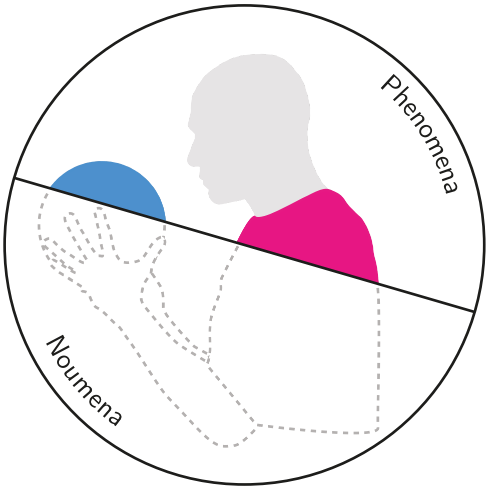


Figure 4. Illustration of Kant's notions of noumena and phenomena with which the former relates to things-in-themselves and the latter to how an observer experiences them through the senses

functionalism (Brunswik, 1952, 1955): functionalism because he emphasised the importance of studying how organisms perform actions (i.e., how they function) in their environments; probabilistic because he argued that the environment is non-deterministic in nature and organisms therefore internalise cues of distal variables in a probabilistic fashion in order to function. Brunswik was a pioneer in bringing ideas of probability into psychology.

Brunswik emphasised the importance of molar, rather than molecular, behaviour, which implies that behaviour of an organism at a given time cannot be explained solely by molecular processes in the moment but the organism's history of previous behaviour in the environment must be considered as it shapes future goals and current actions (Brunswik, 1939). To express this importance of distance in both time and space between an organism and its environment, Brunswik —inspired by Heider (1930)— devised a model using the terms central, peripheral, proximal, distal, and remote to represent levels of distance (see Figure 5). The cognitive aspects of the organism lie centrally, whereas perceptual-motor aspects of the organism exist peripherally. Proximal cues and means available to perceptual and motor processes of the organism are situated in the environment. Beyond mere cues and means, exist the distal objects of the environment that form the basis of the proximal aspects. Beyond the distal, lies the remote, which is aspects of reality currently out of reach of the organism.

Central to Brunswik's psychology is the notion of *vicariousness* or substitutability. Brunswik expressed this both in relation to cues in the environment (what he called *vicarious mediation*) and in relation to means to reach a par-

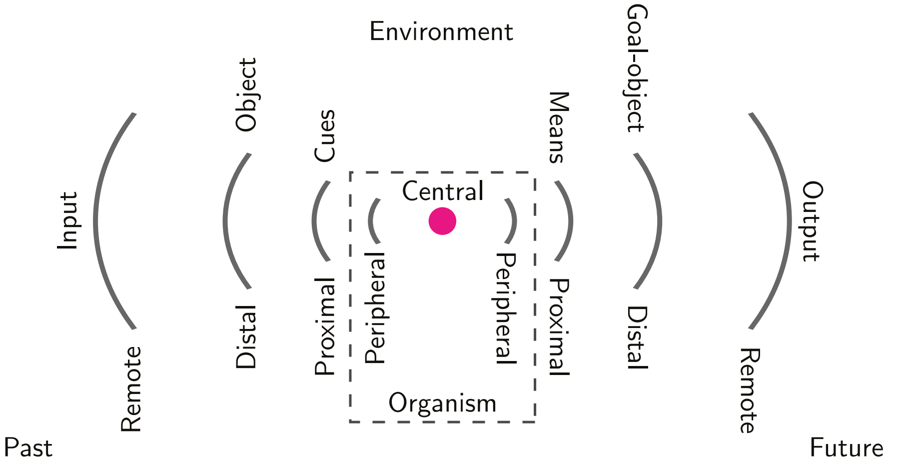


Figure 5. Abbreviated description of Brunswik's organism-environment model. Source: Figure was redrawn from Wolf (2000)

ticular end (what he called *vicarious functioning*). The mediation aspect implicates that many cues can give the organism clues to the underlying distal variable, that is, a variable only phenomenally experienced by the organism that is situated in noumenal reality. From this outlook, the organism can at times substitute, for example, auditory cues for visual cues in determining the origins of the effects experienced. The functioning aspect suggests that many different means can be used by the organism to reach a particular end. This idea of vicarious functioning was not exclusive to Brunswik as it was deemed a fundamental aspect in behaviourism. Hunter (1932), for instance, expressed how, in psychology, much of purposive behaviour can be performed in various ways. Hunter gave the example that if hands are lost, much of their functionality can be replaced by using the feet or even the mouth. He contrasted this with the work of a physiologist who rarely deals with vicarious functioning when studying organs of the human body. The lungs or the heart, for example, have very specific purposes that cannot be substituted by any other bodily organ. The notion of vicariousness demonstrates the adaptability of human psychology in reaching goals, whether it is a central goal of judgement in using cues or a distal goal of behaviour in using tools. Examples of this were found in the study of Paper IV where some train traffic controllers used either a ruler or their hands to guide their eyes visually in reading paper graphs. Vicariousness becomes an even more important aspect in complex information environments, where technology is used as it allows for more possible ways of attaining domain goals. The study of Paper I corroborates this in that multiple strategies were available to achieve certain tasks, with some strategies completely shifting with the introduction of automation.

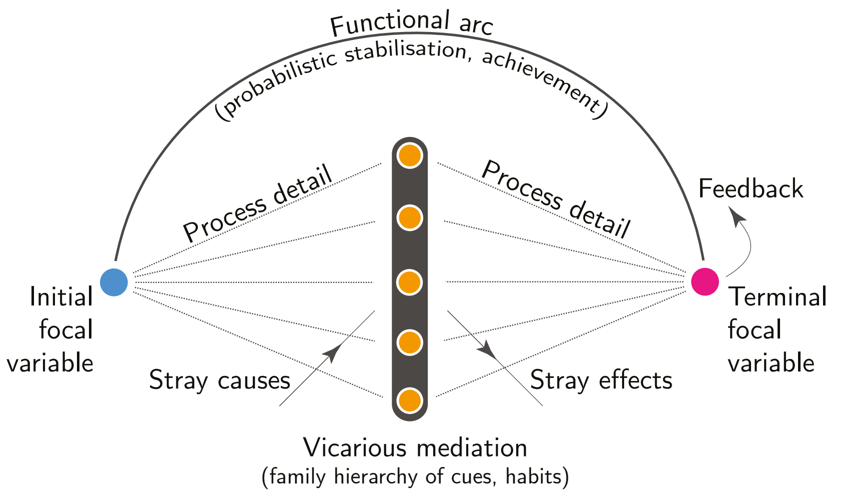


Figure 6. The lens model. Source: Figure was redrawn from Brunswik (1952)

Brunswik illustrated the vicarious aspect of judgement and behaviour in an elaborated version of Heider's (1925) lens model of human perception (see Figure 6). Brunswik's model should be interpreted through either perception or overt behaviour. With regard to perception, the initial focal variable is a distal variable, a noumenon, that, through processes in the environment, scatter cues that reach the organism. From this set of cues, the organism will use a subset to make up the terminal focal variable, the phenomenon. Thus, a judgement is made on the encountered distal variable. As regards to overt behaviour, the initial focal variable is a motivational state or goal from which many possible means are available to the organism. From this set of means, the organism will use a subset to work its way to achieve the motivational state through accomplishing the terminal focal variable (i.e., goal). The model illustrates how the organism works towards a stabilisation between central and distal variables, either through perception in interpreting ambiguous cues from the environment or through action to achieve particular states in the environment motivated by inner objectives. This stabilisation can only be achieved through constant interaction with the environment, resulting in organism actions that, in turn, generate feedback from the environment. The beauty of Brunswik's model lies in this cybernetic relationship between organism and environment. Psychological models tend to be snapshot images of behaviour, but the cybernetic approach places emphasis on the fact that any action of the organism will eventually result in new cues in a future state for the organism to interpret. This is how the organism can then work to stabilise the relation between the initial and the terminal focal variables by constant re-evaluation of cues and means to work towards a particular goal or judgement. The model is an illustration of the adaptive character of perceptual and cognitive processes. Over time, colleagues that work in the same environment will tune into the same environmental cues as a way to stabilise the relation between initial goals and the achievement of the goal in the environment. Even if the knowledge gained in the environment is personal, it is still far from private given that colleagues can verbalise about each other's behaviour as argued in Paper II. Verbalisation by colleagues has been suggested as a useful method to investigate the adaptiveness of individuals in professional settings empirically (Paper III).

Polanyian epistemology — Knowledge as process

The adaptive character of mental processes serves the foundation for learning and knowledge, according to Michael Polanyi (1891–1976). Polanyi (1961) advanced the idea that knowledge is best understood as a process of knowing and should be seen as an activity, expressing that the participatory act of the body in perception can be extrapolated to knowing in the sense that the body functions as a tool in observation and manipulation of objects (Polanyi, 1969). Fundamental to Polanyi's view is that knowledge is personal to the knower and much of the personal act of knowing is in fact *tacit*, which means that the knowledge cannot be expressed verbally.

The concept of *tacit knowledge* is best introduced to the uninitiated reader through the example of riding a bike. This is a kind of knowledge that is developed through practise and cannot be acquired by instruction alone but must be exercised, often with immense effort. To be able to ride a bicycle, muscle control and adaptation to the consequences of the muscle movements must be learnt because the movements result in the bicycle falling to one side and therefore the fall needs to be counterbalanced with further muscle movements. This balancing act produces a constant shift from one side to the other as the bicycle progresses forward; however, once learnt, the act will be made with no conscious effort. This skill is not verbalisable and is certainly not something that can be learnt merely by reading a handbook on bicycling, but it still has the essence of being something known once it is learnt. Much of the knowledge possessed by drivers of commercial vehicles (Paper I), train traffic controllers, or other vocational professionals (Paper IV) is tacit knowledge. This knowledge is developed as the professional works in the designated environment through internalising the experiences of solving tasks within the particular domain. Eliciting and functionally describing the purposive behaviour that results from the tacit knowledge of professionals is a challenge that the methods in Paper I–IV undertake.

Knowledge has traditionally been discussed almost exclusively in terms of propositional knowledge, which refers to assertions that can be expressed and shared. For a long time, knowledge was defined as justified, true belief (Plato, 369 B.C./2006). This view of knowledge was challenged by Ryle (1945) who argued that knowledge can be divided into *knowing that*, which is the traditional idea of theoretical knowledge, and *knowing how*, which relates to knowledge as practical skills a person can perform. Polanyi (1966) contends that these two aspects of knowledge are in fact similar in structure and the one cannot be present without the other. Tacit knowledge does not only relate to practical skills but also in the recognition of objects. When encountering a familiar face, it is instantly recognised. But in trying to understand how the face can be recognised, it will not be possible to explain how this recognition process works. When attending to a known object, the gestalt of the object is made aware to us in its totality, not piecemeal by its constituents. Similarly, when using a familiar tool, the tool itself is barely given any attention; rather, the user's focus lies beyond the tool: on the task at hand or on the distal variable in Brunswiks terminology. A distinction can therefore be made between a comprehensive entity and its particulars (Polanyi, 1961). In relation to face recognition, the comprehensive entity is the face and its particulars are the eyes, nose, mouth, eyebrows and their relation to one another. In relation to carrying out a task, the comprehensive entity is the task and its particulars are the user's muscle movements, the tool and its functionality, and the coordinated activity.

The particulars of a comprehensive entity can be attended to in two ways: (1) focal or (2) subsidiary (Polanyi, 1961). When the particulars are focused on individually, the overall meaning of the comprehensive entity is lost. For example, if one repeats a word enough times and the person focuses on lip movements and the sounds they produce, the word soon loses its meaning and it seems hollow. When the particulars are attended to subsidiarily, on the other hand, they constitute the meaning of the comprehensive entity, which is now experienced as a whole. For example, individual notes played in succession can make up a familiar melody conveying a certain mood. The latter form of attention is the focus in tacit knowing in that particulars are known only in relying on them in the attention of the whole. Polanyi (1966) has dubbed these the proximal and distal terms of tacit knowing, with the reason being that in the act of tacit knowing, the knower attends from the proximal to the distal. The proximal term serves the foundation of the knowledge that is tacit. The terminology of proximal and distal in Polanyi's reasoning is not the same as Brunswik's terminology. However, some similarities can be discerned in that selection of proximal cues is not a conscious act of the perceiver; instead, the attention on the distal object emerges from a subset of subconsciously prevailing proximal cues. The aspect of the proximal and distal terms and the attending from the former to the latter are true also in the performance of a skill. Here, the proximal term can be the muscular acts that are attended to only in terms of the performance of the skill, but there is no awareness of them per se (Polanyi, 1962a). In the practise of the skill, Polanyi asserts that the performer comes to *dwell* in it. By assimilating the proximal term of tacit knowing, this incorporated knowledge extends the body, which leads to a dwelling in the knowledge (Polanyi, 1966). On this knowledge creation process, which results in acquiring new knowledge partly unconsciously Polanyi (1962b, pp. 64–65) writes:

> A mental effort has a heuristic effect: it tends to incorporate any available elements of the situation which are helpful for its purpose. Köhler has described this for the case of a practical effort, made by an ape in the presence of an object which may serve as a tool. The animal's insight, he says, reorganizes its field of vision so that the useful object meets his eye as a tool. We may add that this will hold not only of objects which are made use of as tools, but also of the performer's own muscular actions which may subserve his purpose. If these actions are experienced only subsidiarily, in terms of an achievement to which they contribute, its performance may select from them those which the performer finds helpful, without ever knowing these as they would appear to him when considered in themselves [...] Hence the practical discovery of a wide range of not consciously known rules of skill and connoisseurship which comprise important technical processes that can rarely be completely specified, and even then only as a result of extensive scientific research.

This passage can be condensed into Polanyi's famous phrase, "one can know more than one can tell" (Polanyi, 1966, p. 8).

Distal knowing

Kant's philosophical position, outlined in the beginning of this chapter, is epistemological in nature. He argues that the human can never know the noumenal aspect of the world and therefore he can make no ontological claims. However, if considering the body of an intelligent agent acting in reality, it becomes clear that the acting body is a noumenon in itself. Thus, intelligent agents are able to act in noumenal reality through various acts (e.g., kicking or lifting objects). The body is not just an isolated vessel separated from noumenal reality; rather, it is an integral part of it. The composition of an organism is contingent upon the aspects of reality that has evolutionarily shaped it physically and therefore also cognitively if considering the functional psychology of Brunswik. In his cybernetic model of organism-environment interaction, actions lead to new phenomenal experiences that leave clues for the intelligent agent to interpret. Thus, the agent can learn to understand aspects of the noumenal. More specifically, the act of interacting with reality formulates knowledge structures directly coupled with noumenal aspects, although these cannot be verbalised. Arguing from Polanyi's standpoint, much of what is learnt is tacit, but nonetheless, knowledge about the noumenal will be acquired. Polanyi (1961, p. 467) writes:

> We can account for this capacity of ours to know more than we can tell if we believe in the presence of an external reality with which we can establish

> contact. This I do. I declare myself committed to the belief in an external reality gradually accessible to knowing, and I regard all true understanding as an intimation of such a reality which, being real, may yet reveal itself to our deepened understanding in an indefinite range of unexpected manifestation.

Environment as interface to reality

The human body seems so highly integrated with the environment, where tacit knowing enables what seems like instant interaction between mental goals and environmental means. From this conception, the body is not experienced as an object but rather as the proximal term in attending from it to the distal terms of the world (Polanyi, 1966). Through natural selection over years of evolution, the perceptual system of the human species has been optimised for particular properties of reality that carry vital information for an individual's continued survival. The processes of evolution have therefore tuned all animal species alive today to a particular 'setting' of reality—an *environment*. An environment, as used in this dissertation, constitutes those aspects of reality that directly affects and can be directly affected by a particular organism.

Because the environment is bounded by a perceptual horizon limited by the sensory faculties of the organism, it can be said to have a phenomenal characteristic. It also has a noumenal characteristic because it is bounded by an actual horizon that constitutes affordances, which refers to potential actions that can be carried out in reality, bounded by the size and the composition of the organism's body (Figure 7). Each environment is more similar within a single species than between species of organisms. From this perspective, the environment can be considered an interface between an organism and reality. Just as a graphical interface reveals important aspects of a system to its user, so does the environment highlight certain aspects of reality to an organism. Organisms do not need the 'full picture' of reality to survive and thrive; the phenomenal experience of the world is less rich than its noumenal foundation, but more useful because of how relevant features have been made salient through natural selection and exposure to the environment. The sharpening of the senses to cues in the environment was evident in the experiment in Paper IV, where experienced train traffic controllers quickly identified signal faults in the control system, even though the indication in the interface is quite subtle.

On a larger scale, looking at how humans structure the environment around them reveals something about their psyche (a kind of cognitive reflection process). Humans compartmentalise everything around them by organising and categorising things in their surroundings; thereby structuring and conceptualising, for example, nations, cities, houses, rooms, and drawers. Perceptual and motor processes are far more efficient when applied to an organised rather than a cluttered environment, which frees up resources for higher cognitive processes. Thus, humans constantly redesign parts of reality to improve the efficacy of the environmental interface leading to improved efficiency and effectiveness in their purposive behaviour. Consider the act of driving a vehicle. Today's transport roads are mainly constructed with straight and clearly marked lanes. Moreover, there are clear traffic laws and rules to help individuals in their predictions of perceptual input. Keeping on one side of the road helps in not having to constantly use prediction error processes to avoid oncoming traffic. Signs are clearly marked with bright colours to easily attract attention to inform and remind the driver of basic traffic rules. The design of this whole system serves the driver with cues for predictive processing. All this is done so drivers can quickly navigate using minimal cognitive effort with tacit knowing behind the wheel. Experienced drivers will drive effortlessly, daydreaming or contemplating everyday concerns, suddenly realising that they are approaching the desired destination without necessarily remembering details of the route travelled.

The restructuring of the environment to enable improvements in behaviour and facilitate development of tacit knowledge is at the heart of Human Factors research when working towards design of sociotechnical systems. This goal can only be achieved if the researcher develops a thorough and reliable model of the current work environment and the relationship its operators have built with it through years of practise. Such a model is foundational in novel and non-disruptive redesign of the system to ensure that the overall goal is safely reached with increased efficiency and effectiveness. To formulate a reliable user-environment model, the researcher must observe actions in the environment and thereby experience knowledge first-hand, as manifested in purposive behaviour.

Delineating context and environment

When studying professional users, context and environment are core elements: taking a fish out the water will drastically limit potential discovery of swimming processes. The single most useful predictor for people's behaviour is the environment in which they reside. To identify factors that determine their behaviour, Barker (1968) made observational studies of children. He found that the behaviour of different children in similar environments had less variability than one child's behaviour across different environments.

The concept of context was explored in depth in the present author's Licentiate thesis (Axelsson, 2016), and one central issue needs to be addressed in the present dissertation. A main conclusion of the Licentiate thesis was that context is not so much something a user (or individual) is situated in, as proposed in the Human-Computer Interaction literature and particularly the ISO definition of usability (ISO, 2018). Rather, the author called for a distinction between context and environment. Context is personal and necessary for the interpretation of information available through the environment. How-

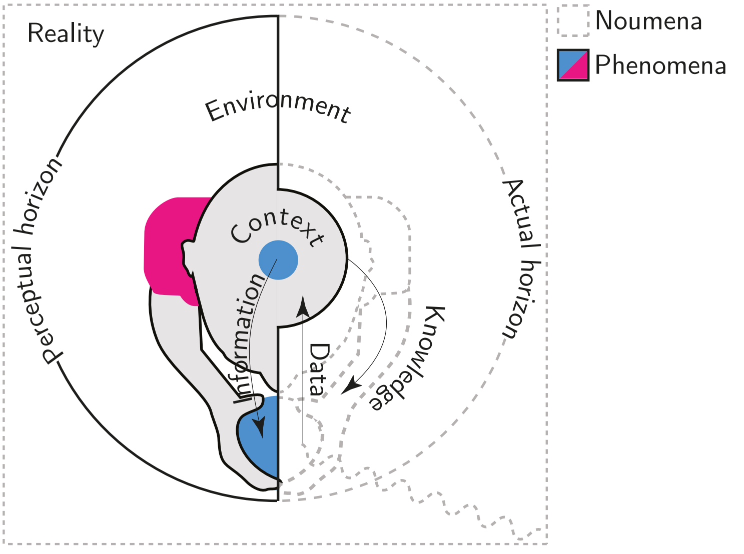
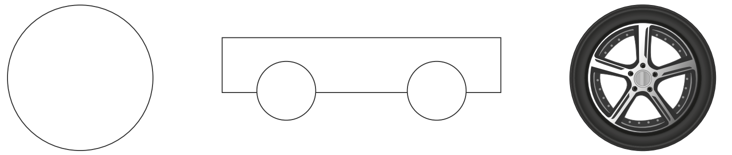


Figure 7. Illustration of the environmental interface and the personal nature of context

ever, the two terms can easily be confused in seeking to understand a user's environment. Actions of users depend on the users' conceptual understanding of underlying processes of the system used. Using a system in environments it was not designed for or not having sufficient understanding of technology, can impede the users' ability to reach intended goals. Designers tend to think of these as contextual factors, but they are only contextual in the meaning that they constitute a conceptualisation of the user's environment concocted by the designer. In other words, the 'use context' is rather a user-environment model held by the designer. What this concept entails is that the designer identifies aspects of the user environment that impede the user's experience by building a mental model of the user environment and interactions therein. This type of conceptualisation of a problem space that a problem solver mentally formulates will be referred to as *contextualisation* (this term will be developed further in the chapter on 'Eliciting professional knowledge').

The relationship between environment and context is outlined in Figure 7. What this figure illustrates is how noumenal objects and events impinge upon the organism in the form of data, that is, proximal cues from the environment (e.g., the number '5'). The data is contextualised and becomes information (e.g., 5 degrees C read from a thermometer). In this process, perceptual systems aid the organism in dressing the world in a phenomenal garment that constitutes the perceptual horizon. This phenomenal information, in conjunction with previously experienced information, serves as the basis for actions through the environment, in that information is now used in purposive behaviour (e.g., putting on thick clothing before going outdoors when the out-



(a) Circle representing a wheel (b) Car composed of primitive shapes (c) Detailed illustration of a wheel

Figure 8. Different abstraction levels of a wheel

door temperature measures only 5 degrees C). It should be noted that reifying the notion of data to a reader is difficult. The '5' used as an example above will automatically be processed as information by a perceiver. The reader is asked to imagine the particulars that make up the symbol rather than its representation as a number in order to grasp the notion of data. The reason why it is difficult to convey this idea of data is that our information-processing system cannot help but interpret and make sense of incoming data, our perceptual systems are tailored to transform data into information. In this way, data is the particulars that Polanyi is referring to and information processes produce comprehensive entities.

Stratified attention

Attention is always stratified in that we cannot attend to everything in our environment at once. Particulars in the sense of proximal cues from the environment will tacitly build a comprehensive entity at the time of focus. But cues from the environment are always ambiguous and the comprehensive entity can therefore shift in terms of what distal object we judge to be present. This kind of contingency is when context becomes important. If the comprehensive entity cannot be fully interpreted because of ambiguous cues coming from the environment, context can be helpful in that it provides a structure for interpretation by evoking knowledge structures related to the incoming cues.

To illustrate this point, consider Figure 8a. It can be insisted that the only thing represented in the figure is a primitive circle. There are no particularly useful details to interpret the figure as anything else. Now consider the same circle being a part of Figure 8b. By guiding attention to the circle in conjunction with other primitives, the circle can now be interpreted as a wheel on a car or a cart. Here, the complete figure serves as a larger whole, a context, to the specific part of the picture. The comprehensive entity that now resembles a wheel is interpreted not only by the particulars that make it a circle but also by the context that helps in the interpretation of the ambiguous symbol, now resembling a wheel. However, if the particulars that compose a comprehensive entity are more detailed, such as in Figure 8c, interpretation will be less ambiguous compared with the case of the primitive circle in Figure 8a.

As discussed above, Polanyi posits that when particulars of a comprehensive entity are singled out, the meaning of the comprehensive entity is lost. This can be phrased differently when considering context and the stratification of attention. With some particulars now in focus, they can instead be considered a new comprehensive entity with its own particulars. The previous comprehensive entity is now a part of the context, similar to how the circle in Figure 8b contributes subsidiarily to the whole as a car and how this car then contributes contextually when the circular part of it is pointed to, and consequently, interpreted as a wheel. Thus, context and particulars are constantly shifting in light of comprehensive entities in a stratification of attention.

Context is based in personal knowledge acquired through encountering certain cues in the environment (a probabilistic relationship). When cues are ambiguous, the perceiver will select the most probable interpretation according to what is most prevalent based on frequency of experience of similar cues. Context is always present and constantly changing as new experiences are gained in the shift between various comprehensive entities. Because experience is gained in interaction with reality through the environment, cues in the environment will trigger different contexts. The context induced by the detailed wheel in Figure 8c is vastly different than the context activated by the circle in Figure 8a. The former is more likely to generate a context of road traffic and vehicles, whereas the ambiguity of the latter can induce many more contexts in the perceiver's mind because this object or shape can be associated with many other objects that have been encountered in the environment.

Performance of a skill will always require focus on the distal term in reaching an intended goal rather than focus on muscular movements. For example, Polanyi often makes use of an example of how a pianist must focus on the music produced in the performance (e.g., Polanyi, 1961, 1962b). If attention is shifted towards movements of the fingers across the keyboard, performance will be impeded and the pianist will lose track of the overarching goal of producing the melody. In this sense, the body is a tool for thoughts. Infants must learn to control their limbs just as more mature children (who have progressed to a higher level) learn to manipulate tools, eventually using them effortlessly. Similarly, without previous exposure to cars or wheels, the interpretation of the illustrations in Figure 8 would be impossible. From this account, growing up in the world and becoming ever more skilled in tool use and conceptual understanding results in a deepening of distal focus into the noumenal aspects of reality. Abstract rules that were once laborious to follow become integrated and second nature as knowledge is acquired through purposeful practise.

Proficiency

Dreyfus and Dreyfus (1980) have proposed a five-stage model of how to become an expert within a particular domain: (1) novice, (2) competent, (3) proficient, (4) expert, and (5) master. The different levels dictate how a learner performs cognitively in the areas of recollection, recognition, decision, and awareness. The novice will start by learning non-situational features of the domain and will be given rules to adhere to in order to make decisions based on these features. Thus, the novice needs to make use of explicit reasoning and effortful thinking to progress to the next level. Here, recognition is rather decomposed in the sense that information cannot be fully absorbed but must be examined one bit at a time, similar to how a beginner of a new language has to consider each word of a sentence to interpret its meaning. As the learner practises the skill, the once abstract and non-situational features of the information will now become concrete and situated for the learner, recognition will be more holistic, and decisions can be made intuitively rather than analytically.

Concerning the level of mastery, it is more of a state of mind than a level of proficiency. Anyone who has reached the level of expert can experience the sense of mastery, which means that the expert is fully absorbed in task. Rather than being an outside observer making decisions or performing conscious actions, masters tend to be one with the environment when displaying their skills in their domain, a complete indwelling in Polanyian terms. An analogy presented by Polanyi (1961) is that of a stick used to probe objects. Over time, the stick becomes more of an extension of the hand in which the user feels only the objects probed, with the stick becoming an integral part of the sensory system. Masters of chess or highly skilled pilots have described the feeling of being submerged and becoming an integral part of the task environment (game of chess or aeroplane system). One of the most experienced participants in Paper IV made a remark at the end of his scenario that attests to this feeling of submergence. He explained how other controllers generally express that the simulator for train traffic control does not feel real. He did not share this opinion but admitted that he initially felt like he was part of an experiment. However, after a few minutes he became fully immersed in the tasks and worked as if it were a normal working day.

It is important to be aware that a high level of proficiency in problem solving does not (usually) necessitate exceptional cognitive abilities: no more than normal cognitive abilities are necessary to achieve proficiency in most problem-solving domains. The crucial aspect is rather spending time deliberately practising within the given domain, resulting in domain-specific experiences that can expand knowledge structures and aid the limited capacity of a person's working memory. However, this position does not imply that working-memory capacity is greater for these individuals in terms of being generally better. For example, de Groot (1978) found that chess masters were exceptional at recalling a chess position after viewing it for even as little as 2 seconds. Chess masters would not be able to achieve this performance, however, if the positions are randomly generated (i.e., if they do not follow the rules of chess). Such a situation would result in the positions not being familiar to the chess masters (Chase & Simon, 1973). This finding is an indication that the chess masters found structure in legal chess positions that minimised cognitive strain in remembering and recalling the chess positions. The reduced effort in visual perception and recall is thereby afforded by the triggering of established knowledge structures.

Generally, what signifies proficiency in most domains is the ability of professionals to quickly extract valuable information at a glance and thus infer appropriate actions with minimal cognitive effort (cf. Recognition-Primed Decision model, Klein, 1993). As theorised by Brunswik, this skill is acquired through years of deliberate practise by a positive feedback process, where the acquisition of valuable cues in the environment is made into larger perceptual chunks, which is made possible by ever-developing knowledge structures. Extraction of information in a particular task environment becomes an automated process over time, so that even more complex patterns can be discovered and processed in task performance (Kellman & Massey, 2013). In this way, distal knowing is achieved and improved as professionals are dwelling in their acquired domain knowledge. Similarly, anyone with the ability to read has become an expert in symbol recognition. By learning individual letters, readers become progressively better at recognising them and start processing the letters together to recognise words, and eventually whole phrases. Once the individual has progressed to this level of proficiency, reading is done effortlessly and unconsciously.

Perceptual maturity

Evidence of this perceptual maturity has been observed not just in reading but also in the general visual processes of professionals. In studies of vision, a distinct behaviour pattern of individuals with higher levels of proficiency has been reported. A meta-study by Gegenfurtner et al. (2011) concluded that experts have superior parafoveal processing and selective attention allocation as evidenced through shorter durations of fixation, a higher rate of fixations on task-relevant areas, and a lower rate on irrelevant areas. Experts also have a shorter time-on-target for fixating on task-relevant areas. Taken together, these observations indicate that experts have a more targeted gaze behaviour when searching for relevant cues in the environment to solve problems or to make informed decisions. Task-related information processing is therefore far less taxing for experts than for novices because experts have the cognitive ability to decode task-specific information more efficiently. In addition, experts exert more targeted searches for vital cues in the environment to facilitate decision making, as opposed to a novice who would perform more exhaustive searches. Experts therefore make use of less, though more purposeful, information in a problem-solving process (Camerer & Johnson, 1991). For example, in eye tracking experiments with experts, it has been shown that gazes on relevant information have higher densities, suggesting that experts learn to filter out redundant information (Jarodzka, Scheiter, Gerjets, & van Gog, 2010). This knowledge of where to fixate is tacit and experts generally cannot express how they come to know where to look. Instead, their focus lies on the distal objective of solving the task at hand. Novices, on the other hand, will work with greater effort and guided by some explicit rules in their pursuit for important information. The ability of experts to filter out redundant information and extract vital cues is transferable to all perceptual abilities in the act and development of tacit knowing. For drivers of heavy goods vehicles, combined perceptual abilities help predict friction on road surfaces. These perceptual abilities are a combination of visual, auditory, and tactile cues.

As to train traffic control, it is not unusual to find that controllers register when colleagues in the room are discussing trains relevant to them (Andreasson, Jansson, & Lindblom, 2018). The work stations are organised in an open office space, usually in the form of a circle. Thus, conversations could easily be overheard. For someone not skilled in train traffic control, the sounds are not recognisable as speech. Yet, sometimes the observed controller can be seen eavesdropping or just shouting out an answer to a question being asked that has not been registered the observer. It is also common to witness the manner in which all those present in the control room turn their attention towards one particular work station as some traffic complications are developing there. An increasing number of the train traffic controllers can be seen slowly move in towards the work station because of their desire for information, similar to how a pack of predators circle their prey. The controllers seem to always be attentive to their surroundings as a means to be prepared for any approaching disturbances on their monitored route.

Proficiency develops from continued exposure to environmental cues coupled with actions performed within a particular domain. Thus, intellectual mastery is often manifested in stored knowledge rather than in complex patterns of logical reasoning via working memory (Sweller, van Merrienboer, & Paas, 1998). Theories of skill acquisition would therefore posit that once information is acquired and actions have been successfully implemented, this information becomes organised knowledge that, with continued practise, can be accessed at later stages automatically by virtue of pattern-based retrieval

(Ericsson & Lehman, 1996). Studies on expertise in different domains have all shown that the difference between beginners and professionals is not superior and general problem-solving skills, but rather experience with a large number of problem states that are linked to appropriate actions that can be instantly retrieved in a problem-solving situation (Sweller et al., 1998).

Experience is necessary but not sufficient

Spending considerable time practising in a domain does not inevitably qualify an individual as an expert. Fisher (1991) offers a clear distinction between experience and expertise. He recognised that studies done in the research of expertise use an imprecise nomenclature when delineating between beginners and experts. Researchers often only make a distinction between novices and experts for the purpose of identifying behavioural differences across levels of proficiency, assuming experience and expertise to be synonymous. However, Fisher noted that individuals can show proficiency in one domain but perform poorly in others because they lack experience. Similarly, individuals can have years of experience without actually being an expert. It all hinges on the quality of the experience and having experience with particular tasks. Research has shown that to become an expert the skill must be deliberately practised, not just performed. Therefore, the nature of the experience is crucial in becoming an expert (Ericsson & Lehman, 1996). Fisher (1991) contrasted being experienced with being a novice to signify the quantity of experience an individual has of a particular domain and being an expert with being naïve to signify the quality of the individual's experience.

One way in which deliberate practise manifests itself is how professionals tend to test their systems. In observational studies performed in the MODAS project, drivers often tested the brakes when driving on different road surfaces. The reason for this breaking behaviour was that the drivers want to make sure that they stay in full control of the vehicle during a delivery. If roads are slippery because of weather conditions or if the vehicle is heavily loaded, the drivers must estimate of how fast they can drive and still ensure safe braking in case of an emergency. This is a strategy to optimise speed for the trade-off between arriving on time and making a safe delivery.

In observational studies executed in the UFTB projects, train traffic controllers were sometimes seen adjusting settings of the switching stations, even though no trains were trafficking the route. The controllers call this behaviour 'exercising the switches'. Similarly, in the eye tracking study of Paper IV, controllers would sometimes play in the simulator between tasks to investigate the differences between the actual system and the simulator. Moreover, conducting studies in train traffic control centres often involved travelling there by train. In case there were any incidents in getting there, controllers showed a keen interest in figuring out reasons for the delays through investigations in their support systems.

These playful behaviours observed in the field are not explicit, intentional practise of the operators to achieve higher levels of proficiency; rather, the behaviours are driven by curiosity about the system and its underlying ecology. Such behaviour has the benefit of advancing the operators' proficiency in the domain. Also, testing the systems in safe conditions prepares the operators for future contingencies.

Playful and investigative behaviour in safe settings is fundamental to develop expertise. Testing personal hypotheses of the underlying nature of a system will help conceptual understanding of the system. This aspect was explicated in Brunswik's lens model (see Figure 6) as a feedback loop from actions of an organism upon its environment which, at a next iteration of organism-environment interaction, serves as a new stimulus for the organism, leading to new opportunities for action or adjustments to ongoing actions. According to Brunswik's view, the organism is a stabiliser of events and relationships. Brehmer (1996) acknowledged Brunswik's notion of feedback from the organism to the environment. Brehmer explains how the arrow representing feedback in Brunswik's lens model (see Figure 6) has often been considered feedback as an opportunity for learning in the organism by other researchers, but Brehmer highlighted how the arrow symbolises manipulation of the environment. Thus, users of a system have the opportunity to test ideas and calibrate the behaviour in the dynamic interaction with the system to update their mental model of the underlying properties of the system. A user prone to exploratory behaviour will experience a larger number of specific situations that can lead to a deeper understanding of the system and that keeps the user prepared. Dreyfus and Dreyfus (1980, p. 5) similarly argued:

> Rather than adopting the currently accepted Piagetian view that proficiency increases as one moves from the concrete to the abstract, we argue that skill in its minimal form is produced by following abstract formal rules, but that only experience with concrete cases can account for higher levels of performance.

This perpetually specified skill of system use is an acquirement of distal knowledge that is crucial in becoming a stabiliser of the system and also the foundation for the skill to adapt.

Routine and adaptive skill

Being prepared and able to handle dynamic environments are important aspects of the expertise of vocational professionals. However, research in expertise has generally focused more on routine skill. Holyoak (1991) argued that research on expertise can be categorised into three stages. It was, in his view, initiated by Newell and Simon's idea of general problem solving (Newell, Shaw, & Simon, 1958; Newell, Simon, et al., 1972). Their aim was to describe domain-independent problem solving through a few, general heuristic methods for serial search. This approach generated the first attempts at formalising and constructing artificial intelligence. The idea of expertise as skill for general heuristic search was soon overturned, however. In the second stage, expertise was viewed in light of practise in domain-specific and routine skills in stable environments. Most of the results in studies of this stage were based on athletic, music, or chess playing performance. The research focused on understanding the development of routine skills through years of practise to achieve the highest performance and quality level. The third stage was initiated by researchers looking at skill development in more chaotic environments.

To make a distinction between routine skill of top performers and the adaptive character of some learners, Hatano and Inagaki (1984) called for the separation of routine and adaptive expertise. The authors contended that in familiar environments, learners can perform effectively with only procedural knowledge without any deeper understanding of how it works. In cooking, for instance, a recipe can be followed and learnt by heart and thus the cooker becomes very skilled in preparing that particular dish without culinary skills or in-depth knowledge in food science. As long as the environment is stable, the performer can display efficient and skilled performance. However, being put in an unstable environment will most likely result in decreased performance. Hatano and Inagaki (1984) assert that to be able to adapt to a changing environment, exposure to and build-up of experience with such changes are necessary. Furthermore, when learners have adopted procedural rules and practised until they no longer have to monitor their own behaviour (i.e., becoming competent in the Dreyfus brothers' taxonomy), they may start questioning the procedure and why certain steps are necessary. Beginning to question and reason about established routines are seeds towards conceptual understanding, which is a necessary component of adaptive expertise along with empirical knowledge and a mental model in which newly acquired knowledge can be integrated. Hatano and Inagaki (1984) claim that empirical knowledge and mental models are reciprocally selective, which means that empirical observations determine the appropriate mental model and, in turn, the mental model constrains the extent of empirical observations. In terms of efficiency, speed, and accuracy, a routine expert is superior. However, to handle new problems, flexibility and adaptability are essential traits that, in turn, demand appropriate mental models with well-developed conceptual structures.

Polanyi's conception that internalisation and indwelling are at the root of the process of knowledge also holds true for adaptive skills. When masters attempt to formulate their tacit knowledge into technical descriptions for an apprentice to follow, most of the skills involved are lost in translation. Following rules and instruction only leaves the apprentice with a watereddown version of the master's expertise. Finding oneself in a stripped down and functionally focused learning environment will not prepare students for the variation they will be exposed to once they graduate and find themselves in the rather chaotic environment of reality. Situated learning, on the other hand, provides the right nourishment for tacit knowledge to grow and flourish and will therefore enhance the development of adaptive skills.

The notion of adaptive skill has implications for studies in more naturalistic settings of work professionals. Experts in professional domains often have to adapt to environmental changes, where they have to apply novel solutions to accommodate problems of a dynamic nature. The term *adaptive expertise* has recently been defined for professionals as, "Timely changes in understanding, plans, goals, methods in response to either an altered situation or updated assessment about the ability to meet new demands, that permit successful effort to achieve intent" (Hutton et al., 2017). Accompanying this definition, the authors described three key elements necessary for adaptive performance: (1) understanding of a situation, (2) actions required to achieve intent, and (3) self-awareness to balance the situational and task demands with the ability of the individual (and the resources at his or her disposal) to achieve the intent.

Eliciting professional knowledge

Knowledge elicitation has its roots in the field of knowledge engineering where it was a part of the larger goal of knowledge acquisition (Cooke, 1994). The aim was to construct systems consisting of computer models of expert decision making in a particular field. In the process of constructing these expert systems, knowledge acquisition was necessary to gather information on which to build a knowledge base. With this base, attempts to mimic the experts' decision-making process were made by constructing an inference engine. The field had its peak of interest in the 1980s and early 1990s, but the systems were never as successful as the experts on which they were modelled (Dreyfus & Dreyfus, 1986, 2005). The methods used for eliciting knowledge are still used within requirements elicitation for systems design.

The aim of knowledge elicitation is to understand a particular knowledge domain by engaging experts in the target domain. Ethnographic methods are employed (e.g., observation, participation, verbalisation protocols, and interviews) to understand as much as possible about the domain. The goal of knowledge elicitation in design research is not to build expert systems but to identify potential improvements in organisational or technological aspects of the sociotechnical system and thus produce a list of requirements for design. In Human Factors, the methods are also used by researchers who wish to understand cognitive behavioural processes, including reasoning and decision making in naturalistic settings.

It can be argued that the traditional view of knowledge elicitation as used in the development of expert systems is one of extraction, which implies that there was an idea of elicitation as a process of transfer. In this view, knowledge was extracted from the experts, collected by researchers, and then manifested in the systems built, resulting in a transfer of the knowledge from experts to the expert systems via the researchers. If considering knowledge as an act and that most knowledge possessed by an expert is tacit in nature, it would explain why expert systems were not particularly successful. Dreyfus (1987) provides a historical account of the difficulty of describing expert knowledge. He gives the example of how Socrates—as described in the Socratic dialogue *Euthyphro* by Plato—wanders from one expert to another asking how they specify the characteristics of their expertise but is continuously met with only examples of particular situations rather than an abstraction of the rules they follow. The same issue was encountered by knowledge engineers some 2000 years later. Samuel (1959), for instance, worked on an artificial intelligence system that could play checkers and while it was able to beat most of the advanced players that challenged it, it was unable to outplay checker masters. The system was based on data from knowledge engineering methods. Samuel blamed the experts that participated in the elicitation process, commenting, "[t]he experts do not know enough about the mental processes involved in playing the game" (quoted in Dreyfus, 1987, p. 22). Edward Feigenbaum, the pioneer of expert systems, expressed, "[a]t this point, knowledge threatens to become ten thousand special cases" (Feigenbaum & McCorduck, 1984, p.82). Even if this account is unsatisfactory, it is probably the most accurate description of expertise. This problem attests to what is argued in the 'Proficiency' chapter that expertise seems to develop from abstract rules to specific cases and therefore becomes a manifestation of elaborate exceptions to the once learned rules.

Abstraction, not extraction

In the field of knowledge management, the notion of tacit knowledge was popularised by Nonaka and Takeuchi (1995). The authors maintain that knowledge can be converted in general and that tacit knowledge can be converted to explicit knowledge in particular. They provide an example of a Japanese company struggling to produce the market's first bread-making machine for home use. When the product's first prototype failed to produce bread at an acceptable standard of quality, one of the company's software developers took on an apprenticeship with a master baker. After learning how to properly knead dough, the developer brought her knowledge to the design team. After a third iteration of the product, it finally produced bread of an acceptable quality. The authors therefore insist that the tacit knowledge from the master baker had been converted to explicit knowledge that was later implemented to produce a quality bread-making machine. This view of knowledge conversion has been criticised by Tsoukas (2005), who pointed to the original idea of Polanyi that tacit knowledge is precisely that, tacit and not, as the authors seem to suggest, "knowledge-not-yet-articulated" (Tsoukas, 2005, p. 12). Tacit knowledge cannot be explained or converted. It can, however, be abstracted in that the functional outcome of the tacit knowledge of an expert can be described and formulated into design requirements. When the software developer learnt to knead dough, it was not that she appropriated the skills of the master baker, but rather she developed her own tacit knowing through functional instructions from, and observations of the master baker. This account might seem like hair splitting, but it is fundamental in understanding the difficulty of acquiring tacit knowledge and the infeasibility of transfer of such knowledge. The resulting behaviour of the finished bread-making machine is not manifested in any expertise on bread making because it will not possess the vital characteristics of an expert. The behaviour will be based on a strict following of pre-defined rules and the machine will only produce quality bread as long as the ingredients, temperature, and other important aspects are kept constant. Just as with the expert system, the complex knowledge of kneading bread possessed by the master baker cannot be formalised in the bread-making machine.

Arguing from this perspective, knowledge elicitation should not be considered an extraction of knowledge, but rather as an *abstraction* in which the resulting purposive behaviour is functionally described rather than the knowledge itself. As with any abstraction, subtleties will be lost. With this view, and considering knowledge as manifested in behaviour, knowledge elicitation can be reconsidered. Instead of elicitation referring to extraction and a transfer of knowledge, it can be characterised as the evocation of relevant behaviour through the inducement of a pertinent context in the expert that results in applied knowledge during a knowledge elicitation session. To phrase it differently, a knowledge elicitor would evoke expert behaviour by asking questions or observing the expert perform tasks in a naturalistic setting, both of which are methods of context-inducement. The resulting purposive behaviour can then be studied and abstracted through functional descriptions. Consequently, the knowledge itself is not observed, but its phenomenal effects can be interpreted by the elicitor and described in abstracted terms.

Context-inducing environments

Individuals reside in environments, not in contexts. In this view, contexts are *subjective* in nature. It is not uncommon for a usability professional to employ verbal usage scenarios to provide context for the users in a knowledge elicitation process with, for example, a focus group. But if context is subjective, as argued here, there is no guarantee that the resulting context evoked in the participants is what the researcher originally intended given that the researcher's context is distinct from the participants'. Instead, focus should be put on creating a natural usage environment or at least provide sufficient perceptual cues to provide a more reliable contextualisation on the part of the participants. One important factor to facilitate contextualisation is to find participants that have a vested interest in the use of the system under investigation and who therefore have usage goals that overlap with the system's intended functionality.

The meaning of a comprehensive entity is gathered from its subsidiaries in a bottom-up fashion in which the meaning of the whole is derived from the meaning of its parts. Context provides a scaffolding in a top-down manner in which proximal cues provided by the environment make past experiences of similar cues available in an underlying interpretive space that minimises ambiguity in the parts for meaning-creation of the aforementioned whole.

In returning to the subject of the stratification of attention, which is discussed in the 'Knowledge-based behaviour' chapter, the notion of context-inducement becomes critical in any human-technology interaction-related field, where the aim is to improve the environment of a user by providing technical solutions. The use of context-inducing environments is important in both usability assessments and knowledge elicitation processes. Although eliciting knowledge through interviews in conference rooms is commonplace, users are dependent on environmental cues to trigger relevant contexts and knowledge. In a classical study of the effects of environmental cues on recall, Godden and Baddeley (1975) had participants learn a set of words whilst being either on land or under water. Half of the participants on land then went into the water and half of the participants in the water were called up on land. After the participants' recital of the list, it was revealed that recall was better in the environment in which encoding had taken place, regardless of whether it was on land or in water. This finding suggests that retrieval is better if it occurs in a similar environment to that in which creation of these knowledge structures took place. Verbal description therefore serves as a poor substitute for environmental cues of other modalities, suggesting that a description of an environment or object in a conference room will not necessarily trigger the same context as actually being in the environment or experiencing the object of discussion. In methods of knowledge elicitation, it is therefore crucial that participants who are consulted are provided with environmental cues that can trigger relevant knowledge structures, thereby enabling them to contextualise the knowledge needed for elicitation of reliable verbal and behavioural data. Naturally, any and all environments induce contexts in the perceiver. Thus it should be clarified that, in this dissertation, *context-inducing environments* refer to environments that provide cues that trigger contexts in participants that are relevant for the purpose of eliciting particular behaviours. In this process, it is central to provide cues to the participants that are relevant to the target environment to ensure that contexts prompted in the participants are as comparable as possible to the intended context of the researcher. As exemplified with the circle and wheel in Figure 8 of the 'Knowledge-based behaviour' chapter, if participants are only provided with ambiguous cues, they are left to choose the relevant interpretation. However, if making the cues more specific, the likelihood of activation of the relevant knowledge structure increases. Ambiguous cues will lead to participants contextualising specific situations that may not be of use, or even misleading, to the researcher.

The best context-inducing environment is the actual workplace of the investigated domain. Performing observations and interviews on-site sitting alongside participants as they perform work will ensure that relevant contexts are already available. This circumstance means that the researcher does not need to provide much of the cues to induce contexts in the participants as these are inherently provided by the work environment.

If participation in work is not practically possible for safety reasons or other concerns, then interviews need to take place in less context-inducing environments. As mentioned above, the most common place is in a conference room.

In this situation, the researcher must work hard to provide an environment that induces the right context in the participants. Pictures or videos of work tasks being performed can serve as a good basis for discussion. But questions and verbal descriptions are also context-inducing, provided that they are well elaborated to arrive at the essence of what knowledge the researcher aims to elicit.

Observations or videos of work performance are a good way of getting a general sense of the work being performed. However, if researchers aim to study a particular task or situation, they are dependent on its occurrence during observations or video recordings. Interviews could be used to gain control over what is to be elicited; however, as noted previously, professionals are not very good at explaining their behaviour. One solution is to use simulators in these instances. In Human Factors, simulated environments are common when the task is to study certain domains. They are often used in training and can also be used in controlled studies. For example, in the MODAS project, a driving simulator was constructed (see Figure 9) to test the developed interface of the automated system. A cab was installed with projections of a road surrounding the cab and a window was employed to project a heads-up display with the interface to the automated system. Usability assessments were made in the simulator with the help of drivers. Using a simulated environment is a good way of inducing contexts in participants in that they tend to well represent the target environment. In train traffic control, simulators are used in education, training, and yearly assessments (see Figure 10). The simulator is programmed by an instructor using designed scenarios that the participant will be tested on. In the experiment of Paper IV, a scenario was designed based on an actual train schedule of a busy weekday morning. The interface to the simulator is largely the same as the one used in the actual work stations of the train traffic control centre.

Methods

In this section, elicitation methods used in the various projects described in the introductory chapter will be presented. What these methods have in common is that they all aim to induce relevant contexts in participants by using cues from the target environments. This objective is accomplished by carrying out the methods in the actual work environment, in places comparable to the work environment, or by using stimuli directly coupled with the work environment. Making use of context-inducing environments is indispensable to accomplish successful elicitation, mostly because they stimulate knowledge structures in the elicitation of professional verbal judgements and statements (e.g., a stimulus-aided conference room or observational interviews). Furthermore, context-inducing environments can evoke decisions and actions repre-

Figure 9. Simulator used in the MODAS project

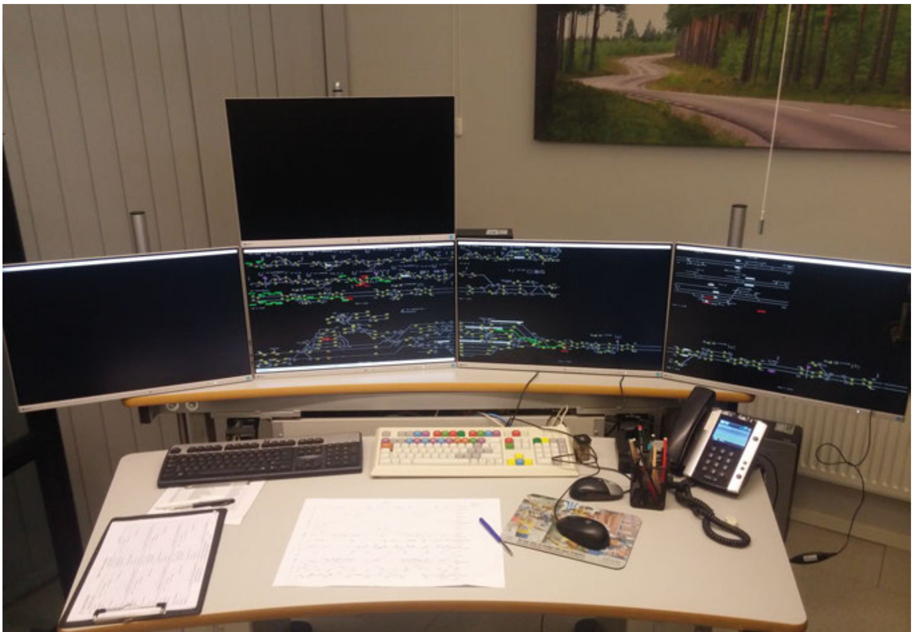


Figure 10. Train traffic control simulator work station

sentative of the work domain for elicitation of professional behaviour (e.g., video-recorded work or use of workplace simulators).

As outlined above, knowledge elicitation methods can serve two purposes: (1) requirements elicitation for input to design or (2) process tracing to understand cognitive behaviour. For requirements elicitation, the methods are used to understand a particular domain and describe it functionally for design purposes for which improvements on the work environment are to be made. Observations and workshops are common methods to learn about a domain and eliciting design requirements. For process tracing, the methods are used to investigate cognitive processes of, for example, decision making or reasoning during task performance to further general theories of human cognitive behaviour. Common methods for process tracing are verbalisation protocols and eye tracking.

Observations

The most common method employed in all projects is observation of operators at work. The best way to get quick insight into the domain is direct observation of the work being performed. Being with the operators to discuss and ask questions when work load is low offers an excellent opportunity to be introduced to the domain and its nomenclature. Here, it is of utmost importance to allow the operators to perform their work and to let them control the conversation. It helps if the operators are highly proficient and have experience with being instructors to, or supervisors of, other operators to ensure that they are familiar with the task of explaining and talking about their work. This ideal scenario is not always possible to obtain in all domains. Heavy goods vehicle drivers, for example, often work on their own and might not converse as much about their work. Hence, they are not expected to instruct or supervise as much as other operators. Other fields, such as nursing, are far more familiar with observational companions in terms of visitors, researchers, or students. On-site observations are very good when the aim is to understand aspects of the work domain or acquire a general introduction. However, being on-site might not always be practical or even possible, or you might want to establish deeper conversations than what is possible using an observation technique. In these cases, workshops can be a good alternative, provided they have a clearly defined goal and that stimuli from the work environment that are related to the topics discussed are introduced.

Workshops

Workshops are helpful in that they prompt users to become involved in discussions. A workshop is a type of seminar in which people gather in a discussion, but they differ from seminars because the aim is to produce some form of

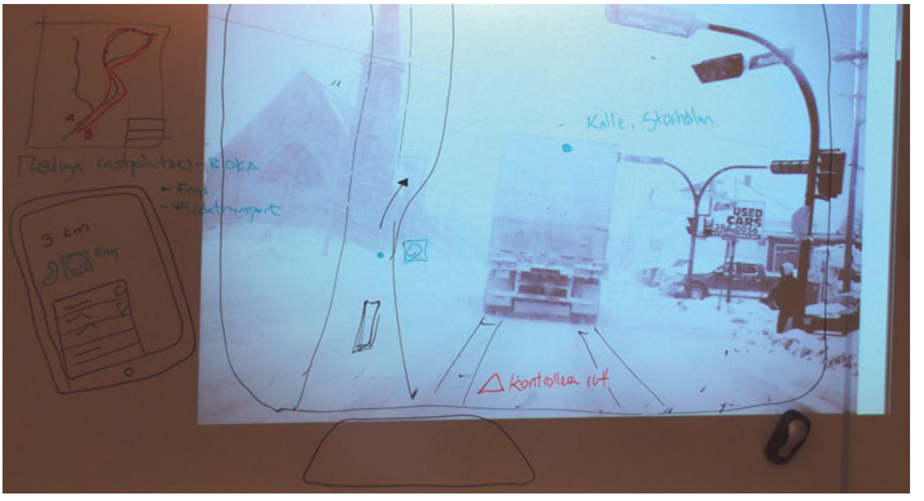


Figure 11. White board during a workshop in the MODAS project

collaborated result. For instance, several workshops were held with drivers in the MODAS project aimed to produce results for a strategies analysis as well as design ideas in collaboration with drivers. The resulting strategy analysis is presented in Paper I. In the workshops, a range of traffic scenarios, represented by photographs, were projected on a whiteboard (see Figure 11). The reason for using projections was to clearly convey the traffic situations under discussion to aid participants in contextualising. Some possible design ideas were drawn on the white board during the workshops where both researchers and participants contributed. Current and potential future strategies to handle elicited tasks from the modelled work domain were discussed and possible future designs to implement the strategies were detailed to serve as input for the design team. To prepare for the workshops, pictures capturing difficult driving scenarios were collected and an iteration of possible current and future strategies was conducted by the researchers. This preparation was important in that these pictures and strategies served as stimuli for the participants' contextualisation. Using workshops is a viable option in early stages of development, such as during requirements elicitation or prototype development. It should not be used as the only form of user involvement or knowledge elicitation, but as a complement to other methods.

Eye tracking

In both the MODAS project and the experiment of Paper IV, eye tracking was used as a research tool in the simulators. Eye tracking is a common instrument for process tracing of mental behaviour and is helpful in understanding both visual and decision-making processes of professionals.

Studies of eye movements have been performed since the latter part of the 19th century, becoming even more popular since the introduction of eye tracking technology in the mid-20th century. Visual perception is the most common way in which humans gather information and eye movement patterns can be revealing as to what is paid attention to and can serve as a window to cognitive processes (Just & Carpenter, 1976). Eye movement patterns are often driven by intrinsic goals to acquire task-relevant information. In a seminal work on top-down cognitive processing, Alfred Yarbus presented the study participants with a picture of the painting 'An Unexpected Visitor' by Ilya Repin. He then gave the participants verbalisation tasks, including 'give the ages of the people shown in the picture' and 'surmise what the family was doing before the arrival of the unexpected visitor' (Yarbus, 1967). Each task resulted in the participants producing distinct eye movement patterns. Yarbus asserts that "during perception many of the elements of the picture are not perceived by foveal vision. [...] Foveal vision is reserved mainly for those elements containing essential information needed by the observer during perception." (Yarbus, 1967, p. 196).

This study of process-tracing illustrates that humans are goal-oriented as regards the collection of information from available cues in the environment. Data from the environment is not processed haphazardly; rather, only data relevant to the information processing task at hand will be considered. The movement of the eyes is an indication of these underlying information processes. Because of the mostly tacit nature of expert knowledge, studying the eye movements of experts can elicit information that cannot be relayed verbally by these individuals. In a review of eye movement studies in medicine and chess, Reingold and Sheridan (2011) found several studies indicating that experts display eye movements that reveal tacit knowledge not clarified by the experts. Even more intriguing was the finding that sometimes the information present in fixations of critical areas do not become consciously available to the expert. For example, radiologists have been found failing to report abnormalities in medical x-ray images, although these experts' fixations indicated that they still differentiated between the missed abnormalities and healthy areas.

Eye tracking today entails using some form of technology that calculates eye movements from capturing images of the participants' pupils, either filmed remotely or by using specially designed glasses with cameras. Because this technique produces considerable data, it is important to have clear predetermined goals and plans. In the MODAS project, the method was used without clear objectives and in the end the data was not analysed. In the experiment of Paper IV, particular eye metrics and specific times of interest were defined prior to conducting the experiment, which is necessary to be able to work methodically with this technique.

Verbal protocols

When the intention is to obtain more detailed information about how work is performed in a particular domain, verbal protocols are very useful. Most common is the concurrent verbalisation protocol (also known as *think-aloud*) in which operators provide an ongoing verbal report of their thought processes during performance of a particular task under study. This technique has the limitation that adding the task of verbalising might interfere with the operator's main task and thus not provide a fair assessment of how the operator would act if the verbalisation task was not included. Another limitation is that if operators are immersed in a task that places a heavy burden on their cognitive processes, they tend to terminate verbalising. Paradoxically, these difficult tasks are often the most important to illuminate in a study.

Another popular verbalisation method is the retrospective protocol in which the operator verbalises after the task has been completed, either by recalling events unaided or with the help of a video recording. A major flaw with this protocol is that operators might not remember precisely what they were thinking and thus start replacing fact with fantasy or, to save face, they might not be honest if they recall that they made some errors that they prefer to conceal.

Conspective verbalisation protocol

To handle these limitations, the TiHR research group developed a new form of verbalisation protocol: operators are asked to verbalise whilst watching videos of their colleagues performing work. The protocol has been termed *conspective verbalisation* to distinguish it from other protocols. In the early days of the protocol, it was discussed whether it should be considered concurrent or retrospective verbalisation, with proponents from both camps. It could be seen as being concurrent verbalising because participants are verbalising as events are unravelling. Alternatively, it could be seen as retrospective verbalisation because participants are verbalising on past events. However, it is important to understand that this protocol is a fundamentally different form of verbalisation in that the verbaliser is a spectator and not the actual performer in the task. The verbaliser could be a colleague or a domain expert. The term *conspective* simply means 'while watching' and is a more precise description of the protocol. Because the performer is not the verbaliser, this protocol manages the issue of emotional investment and demand on cognitive resources. The conspective protocol can then be used in conjunction with either a concurrent or retrospective protocol to form a compound method called *Collegial Verbalisation*.

Collegial Verbalisation

Collegial verbalisation is a method for information acquisition. Crucial to this method is using colleagues during the conspective protocol who share a work

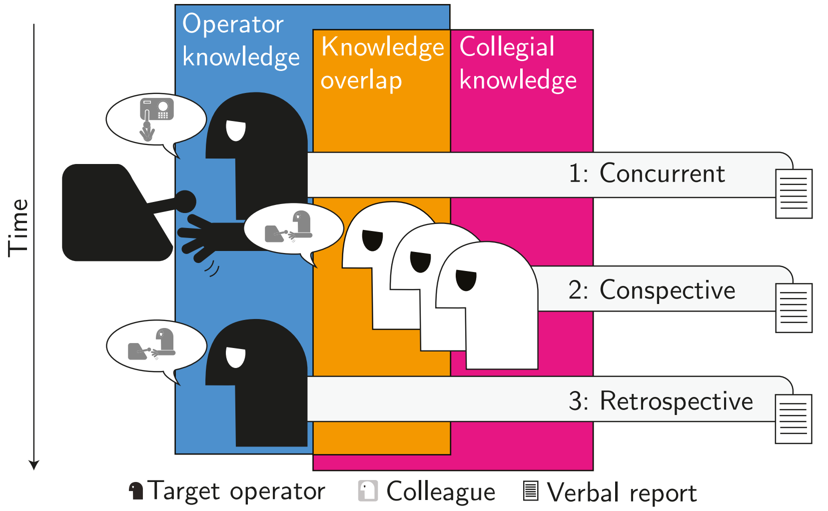


Figure 12. The combination of the conspective verbal protocol with either the concurrent verbal protocol or the retrospective verbal protocol to form the Collegial Verbalisation method

environment, and have done so for many years. It is very important that verbalisers are well familiar with the workplace environment because the environment is loaded with situated cues that, over time, provide similar experiences to the operators. When observing colleagues perform work, verbalisers are able to access generalised experiences of being in similar situations and can therefore explain what might be going on in the mind of their colleagues. The method combines two procedures by using the conspective verbal protocol in combination with either the concurrent verbal protocol or the retrospective verbal protocol (Figure 12). These verbal reports can then be compared with one another, where the combined data creates a more objective view of the elicited knowledge than any of the verbalisation techniques alone. The produced data has an objective character in that the constituent data points have been collected from independent sources of experiences in the same environment. Using only a concurrent protocol or retrospective protocol allows for only one data point for each event. These techniques therefore suffer from a privacy effect which Collegial Verbalisation avoids. However, as already mentioned, the method only works when used with people who have considerable experience working with one another in the same environment as this would entail similarities in contextualisation among the participants.

Part III:
Discussion

RQ1: How can variability and adaptivity in human reasoning be accounted for and how is it affected by context?

In this work, context has been characterised as being subjective and routed in personal knowledge gained in interactions through the environment. Context is therefore seen as active knowledge structures that have been induced by cues through the environment and serves as a network of associated ideas that a problem solver can use to interpret incoming data and make use of in a productive way when solving a particular problem. When the problem solver is thinking, neighbouring associated ideas are available and that can be activated. This associative activation from stimuli in the environment means that a context is fairly stable, but slightly shifting over time as the problem solver acts through the environment and mentally reflects over aspects related to the particular problem.

Consider a situation in which an observer wishes to understand how train traffic controllers perform their work to acquire knowledge about the domain. The oldest form of elicitation is simply asking questions in interviews with expert users: ask what they do, how they do it, and why they do it. A question asked will be data produced noumenally that will reach a listener through the environment and will be contextualised by the listener, which would invoke relevant knowledge structures in the interpretation of the question. This technique is very useful in that it can give a broad understanding of the domain and the character of the work being performed. There are some caveats and challenges to this approach, however. First, every domain has its own nomenclature and the researcher has to be quite familiar with the terminology that makes up the nomenclature in order to later contextualise and understand the respondent's answers. Professional users tend to speak to researchers as though the researchers are familiar with the domain-specific terminology. This way of communicating is done not necessarily because users assume the researcher is familiar with the terminology, but because the nomenclature is a matter of course for them. Every term has many associations to concepts that the professional user is highly familiar with; however, to a researcher, they can seem empty and bear no meaning in that the researcher lacks knowledge structures in which to incorporate the terms used by the professional and hence they cannot be contextualised. The terms can be a part of vernacular language but have a very domain-specific meaning. Familiar words with unfamiliar meanings can make the interviews confusing. If the researcher is not prepared and has not studied the nomenclature, the operator will have to explain much of the terminology.

Furthermore, professional users tend to avoid talking about ‘given’ characteristics of their work unless prompted to do so, either because these are simply obvious and therefore, in their mind, deserve no special attention, or because the users are actually not cognisant of a particular strategy or behaviour that they employ. This elusive aspect of proficiency is what has been previously discussed as *tacit knowledge* (Polanyi, 1966), knowledge that cannot be verbalised but that is integrated with and clarified through non-verbal behaviour. In a study by Eriksen and Kuethe (1956), a person who was given an electric shock when using certain phrases would learn to refrain from using such phrases over time and thus avoid the shocks. When interviewed, the participants were not aware of their behaviour. Clearly, the participants had implicit knowledge about the association between certain phrases and shock administration, but had no explicit understanding of the underlying rules of the administration. This explanation helps account for why experts are not always able to formulate their knowledge in that it is not verbal knowledge they possess, but rather a skill developed in the interaction through the environment. It can therefore be postulated that tacit knowledge is the largest threat to bridging the knowledge gap between a system’s designer and its user.

The differences in contextualisation between an operator and an observer is illustrated in Figure 13. The illustration is an attempt to convey the vastly different perspectives held by two individuals in looking at an interface to a train traffic control system. The operator holds knowledge structures that are activated and cues from the environment are therefore contextualised so that the operator finds meaning in what is being perceived. In looking at the same interface, the observer is overwhelmed by the complexity of the data transmitted and decoupled associations are made to things familiar to the observer but are not domain-specific. Because of this detached view, the interface can appear in complete disarray to the observer but in which the operator sees a clear structure of operating sites, rail ways, signals, and so forth.

Differences between individuals are not only caused by varying levels of proficiency but also from being exposed to different situations, having different learning styles, and having differing goals. Paper IV revealed clear differences in train traffic controllers. When instructors were asked to rank train traffic controllers on a scale of expertise, they were uncertain what variables were most important. They expressed a concern that new train traffic controllers are generally more versed in rules as they have more recently been trained on current protocols whereas more experienced controllers are better at solving general problems. In addition, there are individual differences among experienced controllers as some are more motivated to learn, whereas others are just content to do their job.

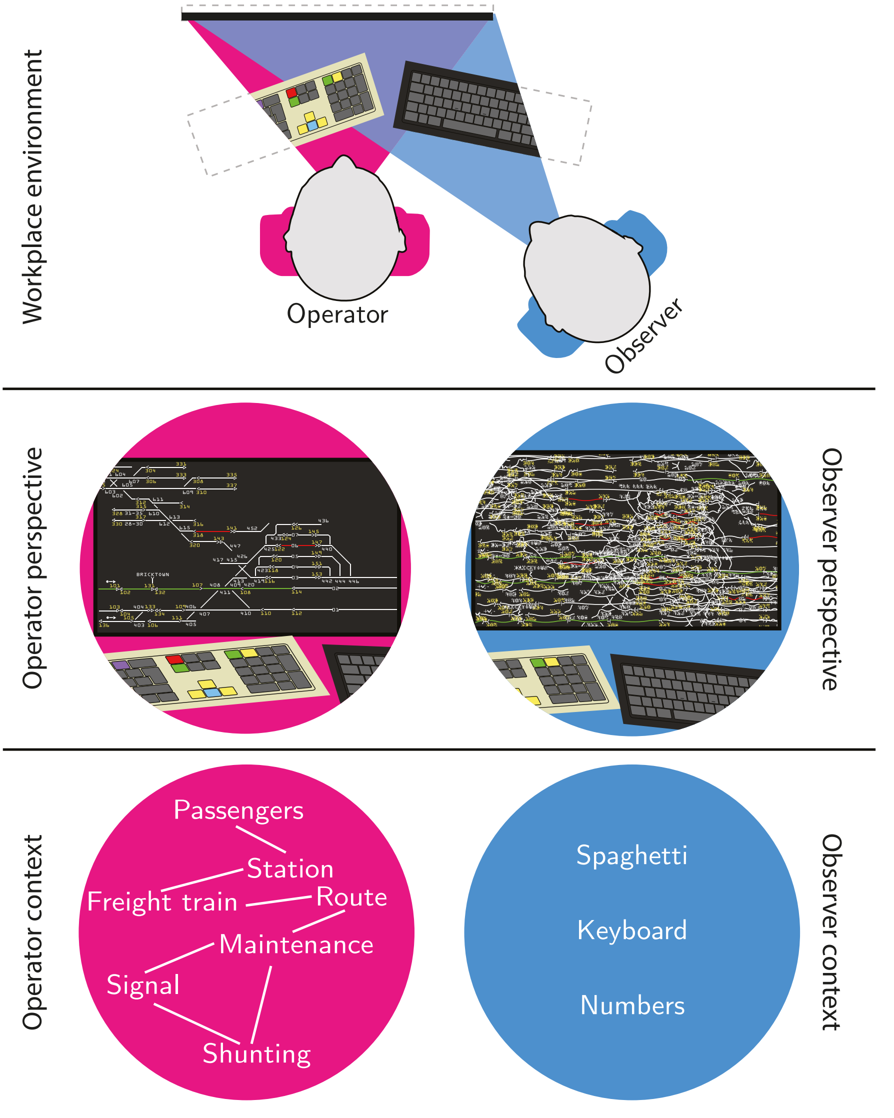


Figure 13. Illustration of perspectives where operators are better able to contextualise information and thus see important structures whilst the observer is overwhelmed because of a lack of relevant knowledge structures to interpret incoming cues through the environment

In Paper III, individual differences of professionals in dynamic decision domains were discussed. Train drivers have different driving styles. Some seek a better understanding of the situation and therefore focus on a time frame of the more immediate future in handling the traffic situation. Others are more reactive in their driving styles, letting the circumstances dictate their behaviour. Unfortunately, the current design of the overall train traffic system does not allow the train drivers much control in that they have very limited information about the general train traffic situation. Some operators have developed their own tools for this, allowing train drivers to access information about surrounding trains, but it is not a general implementation in the Swedish railway system. Such features of the railway system would allow for more drivers to become involved in the traffic situation, which would provide informed decision making to a greater extent and therefore the development of enhanced adaptive skills.

Time pressure, a critical element of adaptive skills, is another aspect that evokes different strategies in human reasoning. The key elements of adaptive expertise discussed in the 'Proficiency' chapter were addressed in detail in Paper III. The main difference from the original key elements is that of *mental time frames*. Various studies carried out by the TiHR research group have produced evidence that expert decision makers contextualise time when making informed decisions in solving complex tasks. Across diverse transport domains, awareness of time critical situations is essential. For train drivers, it is when leaving a station; for high-speed ferry operators, it is when on a collision course; and for train traffic controllers, it is essential to be aware of the history of a malfunctioning train. Time available modulates strategies in these domains and experts learn to stabilise interactions in the trade-off between workload and uncertainty. In train traffic control, when trains are running as scheduled, time will not be a pressing issue and a controller can prepare future meetings and thus work more proactively. However, when interruptions occur, time is limited and the controller has to adopt an executive mode of problem solving. High-speed ferry operators must take actions on very long time scales and therefore time has to be considered. Their strategies will vary substantially depending on where along their route they are currently located and how close they are to obstacles (e.g., whether they are berthing or departing). For nurses in intensive care units, strategies vary on the health condition of the patients and focus lies on stabilising the patients' condition. In critical situations, it is important to be aware of the time frames for available interventions. For drivers of commercial vehicles, strategies depend on possibilities to save time in reaching the destination. Keeping good margins with cars in the vicinity, modulating speed depending on weather conditions, and preparing for upcoming hills are some of the factors considered for timely delivery of goods. In train traffic control, proactive behaviour through preparing train routes will alleviate cognitive strain. However, in the event of unforeseen interruptions, these prepared routes will have to be cleared, leading to the additional work involved in re-planning. Such a situation is something an experienced train traffic controller can handle by not extending the time frames too far, but instead apply a sufficient amount of proactive behaviour. Novice train traffic controllers, on the other hand, generally have a shorter time frame. Novice controllers exhibit more tunnel vision, being only able to focus on the immediate future, whereas more experienced controllers can focus on a larger number of trains as they become familiar with train schedules. Time is therefore an explicit feature in these domains and has to be considered in the application of cognitive strategies to handle the pressure time puts on solving particular tasks.

The view of adaptive expertise proposed in Paper III is therefore a matter of cognitive strategies dealing with the demands of action and recognition abilities, self-monitoring, and time pressure (Figure 14). An elaboration of the key elements of adaptive expertise proposed by Hutton et al. (2017) was therefore made and the following key elements were recognised for adaptive expertise:

1. Actions required to achieve intent and recognition of situational elements are two alternating cognitive activities that go on continuously until some kind of natural closure occurs.
2. Self-monitoring is a third cognitive activity that goes on continuously with the purpose of balancing the situational and task demands with the action and recognition abilities to achieve the intent.
3. Time pressure implicitly regulates (a) the possibility to elicit situational data, (b) the set of possible strategies to achieve intent, and (c) the possibility to execute self-monitoring efficiently. Time pressure must therefore be explicitly considered by the expert.
4. Individual differences in the ability to adapt strategies affect the quality of conceptual understandings and, as a consequence, the ability to reach both general and specific goals.

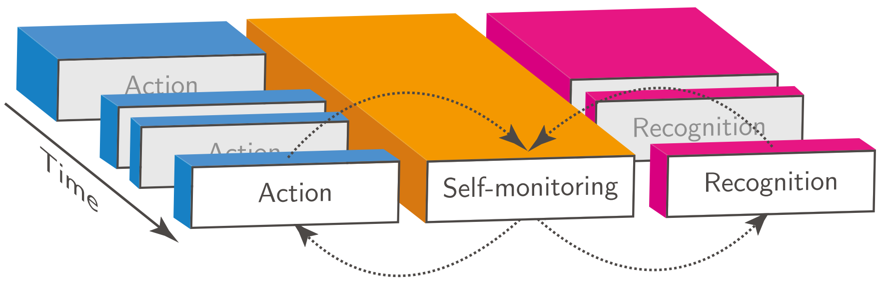


Figure 14. Illustration of how experts contextualise and adapt to a problem-solving situation over time

RQ2: What is the environment's role in the development of knowledge?

Expertise lies in the particulars and not in generalised and abstracted functional behaviour. Moreover, it is manifested in the interaction with the environment. When novices bake bread, they will follow general rules to combine the right ingredients. Instructions or recipes can be considered abstracted knowledge that focus on the critical aspects of bread baking, which accounts for the largest variability in results. In baking, it is the combination of flour, water, yeast, salt, the act of kneading to produce gluten, the temperature, and time in the oven. But other factors are also important, such as temperature and humidity of the baking room, which affects how dry the dough will be. With experience, a baker will learn how a dough should feel to the touch, and the baker will learn to adapt to these variations in the baking process by, for example, adding more water to the dough if it is too dry. The experienced baker learns to adapt to the environment and stabilise the outcome with the intended goal of a particular consistency in the bread.

The act of knowing produces information that can be interpreted by observers. The observers can be the actors themselves, and the observation of their own behaviour results in learning. Therefore, learning is not exclusively performed in particular learning environments; learning is a continuous process. Knowledge is acted out, resulting either in new knowledge structures or reinforcement of already established structures.

According to Dreyfus and Dreyfus (1980), there are two paths to learning: (1) trial-and-error and (2) instruction. Thus, either learners try until they succeed or they can make use of a manual or obtain help from an experienced teacher Another way to phrase the two paths to illustrate why both approaches are necessary is to consider trial-and-error as *exposure* and instruction as *abstraction*. First, the learner is exposed to reality and acts towards achieving a goal by reinforcement of a knowledge structure through failures and successes. This form of acquisition, which can develop tacit knowledge, is manifested in learning by doing. Second, learners can formulate theories of their behaviour by the way of the abstraction of rules and facts once they have been exposed to many situations. These abstractions can be expressed to others (e.g., a student) to help them achieve goals quicker. This path entails active reasoning with oneself or with the student. Such acquisition, which develops verbalisable knowledge, is manifested in learning by teaching. By acting and being exposed to the results of actions, followed by a reasoning process about the results, both skill and understanding will develop. In the beginning, learners will only be able to reiterate what they have been exposed to; however, once they start to reflect about their behaviour, they will be able to describe some functional aspects of the environment and their behaviour, which is a form of self-teaching. Learning by doing refers to the development of a skill through acting and being exposed to the results of these actions, whereas learning by teaching refers to the development of understanding by either thinking about performed actions or explaining the actions to someone else.

The environment in which persons reside has a great impact on their behaviour. Therefore, systematic investigations of individuals exposed to different environments will provide important insights into overall cognitive and psychological behaviour. Conversely, systematic investigation of several individuals in the *same* environment will give significant insights into the structure of that environment. Even if knowledge is personal, it is not entirely private; individuals who experience the same noumenal objects will develop similar knowledge over time in interaction through the environment.

It has previously been established that context is subjective. However, when operators spend time working on similar tasks in similar environments, the resulting knowledge will also have similarities. This position is the theoretical idea underlying the Collegial Verbalisation method outlined in Paper II and proposed as a method of inquiry into adaptive expertise in Paper III. The method makes use of the fact that context and knowledge are tightly intertwined with structures of the environment. Using this method, a researcher will learn a good deal about the structure of the environment in question. The theoretical model underlying the protocols of Collegial Verbalisation is depicted in Figure 15. The idea is that target operators are acting (▲) on stimuli (•) in their work environment; the behaviour is captured on video and serves as stimuli for later verbalisers. If a concurrent verbal protocol is used, the conspective verbalisation sessions are performed with muted recordings. All operators in the verbalisation sessions are well familiar with the work environment. The entire workplace and worker interaction environment are viewed as a generalised knowledge structure held in each operator. When a target operator is working, the specific situation becomes integrated with previously abstracted knowledge structures, which are also offloaded in the form of a verbal report if the concurrent verbal protocol is used. If a retrospective protocol is used, it can be performed immediately after completion of the work task. Thereafter, the knowledge of the situation will be more readily available to the verbaliser, contextualised with the help of the video recording. The longer the gap between performance and verbalisation, the more abstracted the particular situation will become. This course of action occurs because it is incorporated into the operator's knowledge structures that hold knowledge of similar experiences. Concerning the conspective protocol, only knowledge structures of similar situations will be available to the verbaliser, as this per-

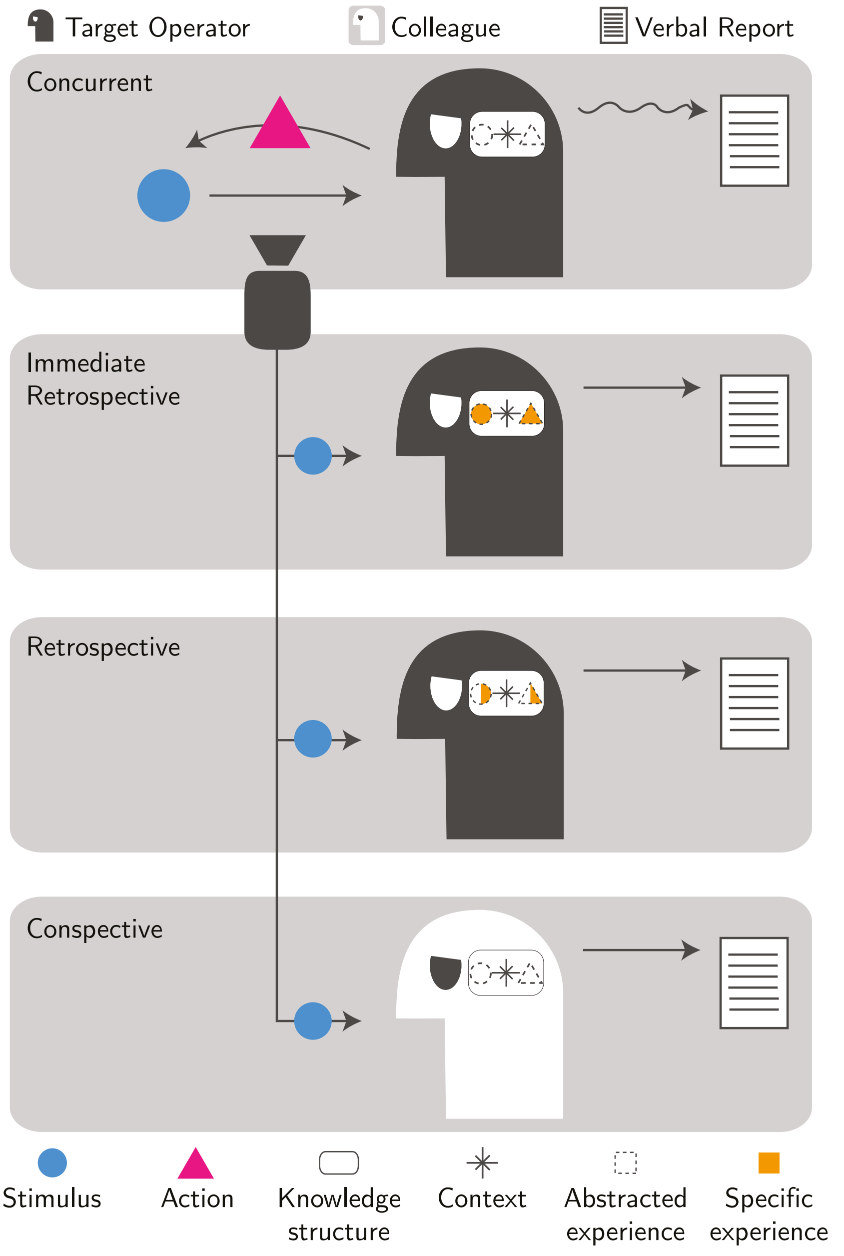


Figure 15. Similarity in knowledge structures of operators based on the experience of similar environmental interactions

son has not directly experienced the specific situation in question. Instead, data in the form of educated interpretations of a colleague's behaviour will be collected and compared between different verbalisers.

Because these individuals share the same work and task domain, they are well qualified to interpret what goes through the mind of their colleagues. Because different individuals will bring varying experiences that they can verbalise, making use of several colleagues will ensure a fairer and more accurate picture. Collegial Verbalisation is a well-suited method for collecting detailed information about a work domain. In addition, because it makes use of video recordings of performed work in the target environment, it is context-inducing by design. The method denotes that researchers will have several verbal accounts of the same operator's work, and it is a systematic way of understanding how tasks are performed in the work environment.

That the verbalisers are sometimes realising aspects of their work for the first time during this procedure cannot be ruled out, especially given that knowledge can be acquired through learning by teaching. In an elaboration of the Collegial Verbalisation method in bedside nursing, it has been suggested that the method could be used to facilitate discussion among staff and thereby be used as a tool for learning in safety critical environments (Löscher, Jansson, & Fröjd, 2019).

The study presented in Paper IV investigated established hypotheses of visual expertise in a natural task setting. In the study, a simulator for the training of train traffic controllers was used as the setting to study eye behaviour across levels of proficiency. The study is highly unconventional in that it uses a dynamic decision task scenario (most studies of visual expertise make use of controlled environments and static stimuli). The idea of the study was to make use of more unstructured tasks, leaving freedom to the participants to act naturally to investigate whether eye behaviour found in more controlled environments would surface under these conditions. The study showed more established correlations between eye behaviour and years of experience compared with variables more indicative of domain expertise. Other variables were investigated (e.g., ranking of participants by instructors and a measure of proactive behaviour reflective of quality of task solutions). However, these measures did not correlate as well with traditional metrics of eye behaviour as years of experience.

The study identified two other metrics of perceptual matureness: (1) use of visual guides to determine time and place of train locations and (2) detection of a faulty signal in the system. These variables had stronger correlations with years of experience as well as the other metrics of expertise than did the more traditional visual metrics. However, correlations with years of experience were stronger.

These findings suggest that proficient information seeking behaviour (in this case, concerning visual expertise) has probably more to do with prolonged exposure to the environment pertinent to the domain of train traffic control than the actual expertise in performing the train traffic control tasks. This conclusion is based on the evidence that other measures that are more related to how work is performed show a weaker correlation with eye behaviour than years of being employed as a train traffic controller. Thus, some individuals with many years of experience still did not perform as well as those with less years of experience in controlling the simulated train traffic as measured by proactive behaviour. It is plausible to suggest that expertise in this domain, it can be argued, is therefore a qualitatively different aspect of expertise, possibly related more to cognitive strategies than to perceptual processing. The example of the use of visual guides affirms the Brunswikian concept of vicarious functioning: the ruler or just the hand can act as a guide. The decreased use of visual guides over years of experience verifies the Polanyian idea of tacitness in which the visual guide is internalised and eventually no guide is needed, that is, only brief and directed glances at the paper graphs are required. However, to reach levels of expertise more than perceptual guides have to be internalised. Being able to quickly locate and identify vital information is a good start. Yet, in the end it comes down to what the operator does with the information acquired. More distal knowledge in terms of cognitive strategies to achieve better problem solving is also needed. For this to develop, an active search of the system for these solutions is imperative.

RQ3: How can knowledge elicitation processes aid in Human Factors research?

Elicitation methods are most relevant when the aim is to investigate a domain. This procedure can be done by probing the territory to better understand the environment of the subjects of study. These methods are not only extremely useful in Human Factors as a foundation for design processes but they are also crucial for researchers attempting to conduct more systematic investigations of human behaviour in applied settings.

User-centred design approaches aspire to structure the environment for the benefit of users. In doing so, the need for iterative design has been recognised in that products developed must be tested at several stages of development to ensure that the final product does not inhibit user experience. This is an evolutionary process driven over time in a progressive manner. Rogers and Ehrlich (2008) quote the French philosopher Alain (Émile-Auguste Chartier) who suggested that boat design was subject to natural selection:

> Every boat is copied from another boat... Let's reason as follows in the manner of Darwin. It is clear that a very badly made boat will end up at the bottom after one or two voyages, and thus never be copied... One could then say, with complete rigor, that it is the sea herself who fashions the boats, choosing those which function and destroying the others. (p. 3417)

It might be argued that today's systems development, manifested in iterative design, makes use of artificial selection. However, it is the situated use and the environment that together provide feedback to a developer of what works and what does not. What to change is easy to discover, but how to change it is often more challenging to determine. When working to incorporate or develop novel technology in a system, it can be difficult to understand the impact the technology will have on the work environment or the work domain as a whole. This situation creates a problem in the design process in that it becomes burdensome to assess the impact a particular design choice might have in the transformed work domain. This problem is well-known within Human Factors and is referred to as *the envisioned world problem* (Dekker & Woods, 1999).

In the MODAS project, the self-driving technologies employed afforded that the tasks would drastically shift within the work domain as automation would take over much of the tasks from today's driver. The project made use of Cognitive Work Analysis, and in the initial phases of modelling the

Figure 16. Overview of the MODAS display

work domain, many hours of driver observations were performed as well as Collegial Verbalisation sessions. However, the Strategies Analysis phase was more difficult as the strategies used in the work domain today might not be suitable in a future automated world. This meant that possible future strategies of the human-automation system had to be identified in the project. The strategies analysis of Paper I proved a valuable input to the design process in collaborating with drivers in a context-inducing workshop.

In the interface for the highly automatic system developed in the MODAS project, time scales of drivers were given consideration in the final design (cf. Paper III). Figure 16 illustrates the final design of the project. The top section of the heads-up display represents planning and information along the entire route for strategic decisions; the left section represents the traffic situation for tactical decisions; and the middle section displays augmented aspects of the immediate surroundings for operational decisions. The work carried out in the MODAS project exemplifies the importance of elicitation methods for interface development.

Making use of context-inducing environments and studying humans in more naturalistic settings can also help develop a more sensitive and deeper understanding of human behaviour. In eye-tracking studies of expertise, it is common practice to use years of experience as a proxy for expertise. The novices used in the studies are sometimes individuals with neither skill nor conceptual understanding of the task or domain they face. Thus, it makes it difficult to obtain a clear view of expert eye behaviour and how it differs from individuals with lower levels of proficiency. The results of Paper IV support this contention. Adhering to the classification of experienced and expert by Fisher (1991) is a good start, but using more accurate phrasing of the inexperienced in these studies could help in clarifying results of future studies. It is crucial to use a carefully considered nomenclature when studying expertise to understand what aspects can be attributed to visual expertise and what aspects need a fuller understanding.

One possible solution would be to propose using the terms *inept* and *ignorant* to signify inexperienced and uninitiated individuals, respectively. Distinct eye-movement behaviour might be a feature of expertise but it could also signify only experience of the target domain. Today's studies in eye tracking across levels of proficiency cannot capture these differences if they do not employ a more delineated nomenclature. Thus, it can be contended that future studies can make use of a taxonomy of *inept persons* (individuals with no exposure), *novices* (individuals who have been subject to some exposure), and *experienced persons* (individuals who have been subject to a sizeable amount of exposure to the target environment). Synonymously, future studies can make use of a taxonomy of *ignorant persons*(individuals with no conceptual knowledge), *naïve persons* (individuals with some conceptual knowledge), and *experts* (individuals with vast conceptual knowledge of the target domain). Such a taxonomy would help in separating particular aspects of expertise seen in different domains. The main idea in such a classification is that in some domains going from being inept to novice will result in logarithmic learning curves in information seeking abilities with learning diminishing rapidly once the individual reaches an intermediate level of experience. In such domains, expert eye behaviour is not actually indicative of task performance expertise even if high effect sizes are observed when visual experts are compared with inept persons on eye tracking metrics. What the study of Paper IV illustrates, of which this nomenclature of proficiency is derived, is the value of using knowledge elicitation methods to discover human purposive behaviour in Human Factors research.

Quantitative methods (such as eye tracking) are very limited in what they can add in our understanding of expertise. Such a method must be driven by theory; otherwise, any data collected will be unclear and difficult to interpret. Quantitative results must be considered in view of current theories. The conspective protocol and Collegial Verbalisation, outlined in Paper II, can serve as a valuable input and inspiration to theories on expertise (as put forward in Paper III). The strength of using many independent observers allows qualitative data to be quantified between individuals to build a stronger theory of the work environment. It should also be possible for eye tracking and Collegial Verbalisation to combine efforts to falsify statements on collegial behaviour. This is a possible path for future studies.

Conclusion

The major contribution of this dissertation is its novel view on knowledge elicitation as an abstraction process. This theoretical view has emerged by consolidating features of Brunswikian psychology with those of Polanyian epistemology. The model of purposive behaviour depicted in Figure 7 illustrates Brunswik's cybernetic relationship between the organism and its environment. It shows the difference in the noumenal manifestation of the body, situated in reality, and the phenomenal character of experiencing the environment and oneself. The model is also inspired by Polanyi's view of personal knowledge in highlighting context as a subjective knowledge structure of personal experiences that is formulated tacitly over time in the interaction with noumenal entities. In this cybernetic view, the acting noumenal body creates phenomenal cues that can be interpreted by agents to enable them to reason about potential actions through pattern recognition in the interaction through the environment. In this view, knowledge is characterised as a personal process of knowing. Tacit knowledge cannot be described or transferred. However, learners can be inspired through the process of experiencing other individuals' purposive behaviours and thus build their own tacit knowledge in practising particular skills and develop conceptual understanding through reasoning about the learning process. Knowledge elicitation is a process making use of observations, questions, or more structured process tracing methods in context-inducing environments to elicit purposive behaviour from the observed individual. Functional descriptions can be produced in this process that furthers conceptual understanding of a particular domain. In Human Factors, knowledge elicitation is used to improve our understanding of human behaviour or to restructure the environment for users to improve their ability to achieve their goals more efficiently, effectively, and safely.

The present dissertation underscores the importance of representative design (Brunswik, 1956). Because of the importance of exposure to the environment and the personal character of context, humans must be studied in environments they have personal experience of to ensure that the behaviour elicited is relevant to the aim of the study. The view of knowledge and its resulting behaviour proposed in this thesis does not only serve as a theoretical foundation for knowledge elicitation. It can also serve as a theoretical justification for why user-centred design is so important, why iterative design is necessary, and, most importantly, why designer-user knowledge gaps will always persist. For anyone determined to make use of knowledge elicitation methods in functional descriptions of the tacit dimension, the following advice can be offered:

- Ensure that the method is performed in an environment that induces relevant contexts for the purpose(s) of the study to elicit behaviour founded in relevant knowledge structures of the participant.
- Cover a range of personal experiences by tapping into several independent statements of the same tasks or situations from individuals who are highly familiar with the target environment.
- Draw on several elicitation methods across levels of analysis by collecting data on both skill and conceptual understanding.

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I would like to start out by expressing my deepest gratitude to my main supervisor Anders Arweström Jansson who supported and guided me these 5 years. You were always looking out for my academic as well as personal wellbeing and I am forever grateful for the opportunity to work under your supervision. Special thank yous go to my cosupervisors Mats Lind and Annika Wallin whose scientific rigour and constructive commentaries have been enormously helpful in my academic progress. A special thank you also go to my senior team consisting of Ingela Nyström and Joakim Lindblad.

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Anton Axelsson
Uppsala, 2019

Sammanfattning

Människa-datorinteraktion är ett multidisciplinärt ämne som sammanför datavetenskap och psykologi där vi försöker förstå hur människan fungerar i vardagen för att kunna bygga teknik som är tillgänglig och användbar för tilltänkta användare. Jag har under mina dryga 5 år som doktorand forskat om professionella användare i komplexa informationsteknologiska miljöer. De huvudsakliga yrkena jag har studerat har varit lastbilschaufförer och tågtrafikledare. Det har resulterat i ett antal publikationer varav 4 utgör grunden för min avhandling. De 4 artiklarna har alla koppling till det som slutligen blev det huvudsakliga ämnet för min avhandling, nämligen *kunskapselicitering*.

Elicitering i det här fallet betyder *frambringande*. Kunskapselicitering är olika former av metoder där forskare försöker frambringa kunskap hos individer som är experter inom ett specifikt område för att vi ska lära oss mer om antingen individen som agerar inom denna domän, och därmed förstå oss på psykologiska och kognitiva processer som ligger till grund för individens agerande, eller så vill vi förstå oss på domänen och miljöns utformning. I slutändan ska informationen vi samlat in leda till förbättringar i arbetsmiljö genom att skapa eller förbättra tekniska lösningar.

Titeln jag har gett min avhandling är "Knowledge elicitation as abstraction of purposive behaviour". Översatt till svenska är det ett påstående om att kunskapselicitering bör ses som ett sätt att frambringa och beskriva målmedvetet beteende hos domänkunniga. Vanligtvis brukar kunskapselicitering beskrivas som en *extraktionsprocess*, alltså att kunskap utvinns ur experter; att kunskap förflyttas från experten till observatören. Jag vill med min avhandling hävda att detta är en grov förenkling och en rent av missvisande beskrivning. För att argumentera för denna syn på kunskapselicitering har jag i min kappa utvecklat ett resonemang kring kunskap grundat i två huvudsakliga perspektiv: Egon Brunswiks ekologiska psykologi samt Michale Polanyis idé om tyst kunskap.

Ekologisk psykologi är en inriktning inom psykologin som inte bara nöjer sig med att beskriva hjärnans struktur för att förstå en individs beteende utan lägger stor vikt vid strukturen i miljön i vilken individen verkar. Grunden för Brunswiks psykologiska syn ligger i målmedvetet beteende. Alltså att individer söker mening i strukturen i miljön omkring dem och arbetar för att föra sig i den och manipulera den för att uppnå specifika tillstånd som motsvarar ett uppsatt mål. När en individ har ett mål så arbetar denne för att stabilisera förhållandet mellan det tilltänkta målet och tillståndet i miljön. Om jag vill tillfredsställa min hunger kommer jag att agera på ett sådant sätt att jag successivt arbetar mig mot något ätbart och strukturen på miljön kommer att diktera mycket av mitt beteende. Vad jag har för mål kommer att diktera vilka objekt i miljön som är relevanta och miljön kommer att forma mitt agerande i mitt försök att uppnå mitt mål, därmed uppstår en växelverkan mellan individens mål och miljöns tillstånd. Denna syn på psykologi är en så kallad *cybernetisk modell* vilket innebär att handlingar har konsekvenser, dessa konsekvenser blir i sin tur information (feedback från miljön) inför nästa handling.

Detta möjliggör att vi kan lära oss och utveckla expertkunskaper. Genom att se konsekvenser av vårat handlande så kan vi forma idéer om huruvida vårt agerande tillfredsställde vårt tilltänkta mål. På så vis kan vi forma kunskap. Under närmare 2000 år sågs kunskap vara "rättfärdigad, sann, tro". Detta var en definition som framkom i en av den grekiska filosofen Sokrates dialoger och ofta när vi pratar om kunskap så menar vi teoretisk kunskap, alltså sådant som vi kan uttrycka och diskutera. Men 1945 lade den brittiske filosofen Gilbert Ryle fram tesen att kunskap bör delas in i *veta att* och *veta hur*. Veta hur refererar här till praktiska färdigheter. På 60-talet myntade Michael Polanyi begreppet *tyst kunskap*. Vad som menas med tyst kunskap är sådant vi vet utan att egentligen kunna uttrycka det i ord. Cykla är en sådan kunskap, det är inte något som går att lära sig utan att praktisera det, du kan inte läsa en bok om hur det går till att cykla och plötsligt kunna göra det. Inlärningen måste ske på en cykel genom en komplex interaktion mellan dina motoriska förmågor och miljön.

Vi befinner oss i en informationskaotisk verklighet och våra handlingar begränsas av utformningen av våra kroppar och lika så begränsas våra upplevelser av utformningen av våra sinnesorgan. Hjärnans uppgift är att finna mönster och skapa kunskapsstrukturer för fortsatt gynnsam interaktion med omvärlden. Ju mer vi interagerar med omvärlden, och ju mer erfarenheter vi skaffar oss, desto mer utvidgas vår kunskap och vårt medvetande. Enligt Polanyi är kunskap högst personlig och mestadels tyst och därmed implicit. Utifrån det här synsättet har jag utvecklat en syn på begreppet *kontext* som något högst subjektivt. Inom fältet människa-datorinteraktion är det vanligt att se kontext och miljö som mer eller mindre samma sak, men för mig är det viktigt att dessa två begrepp hålls isär.

Denna syn på personlig kontext blev uppenbar för mig den dag jag började observera tågtrafikledare i operativ miljö. När jag som observatör tittar på samma skärm som operatören ser jag helt andra saker än operatören. Operatören ser tydlig information, strukturerad utifrån driftplatser, signaler, underhåll och växlingsplatser. För mig ser skärmen mest ut som ett virrvarr av symboler och siffror. Operatören har genom åren lärt sig tolka informationen i miljön och därmed "kontextualiserat" den, alltså funnit en struktur i informationen som nu har betydelse. Men för en novis som mig är informationen överrumplande. Det blir därmed uppenbart att kontext, alltså det som underbygger vår möjlighet att tolka mening i miljön, är högst personlig och därmed subjektiv.

Inom systemutveckling är det inte ovanligt att kunskapselicitering sker i konferensrum. Men ur ett ekologiskt perspektiv är detta inte en god idé. Det kan vara svårt även för en expert att minnas relevant information när denne befinner sig utanför sin miljö. Det är därmed en fördel om kunskapselicitering sker i kontext-inducerande miljöer. Helst då i arbetsmiljön, men om det inte är möjligt bör en liknande miljö återskapas genom att använda bilder, filmer eller simulatorer för att hjälpa deltagarna att kontextualisera relevant information. På så vis ökar chanserna att representativa kunskapsstrukturer aktiveras och informationen som frambringas blir mer relevant.

En eliciteringsmetod som används med framgång av vår forskargrupp och som jag har arbetat med på ett teoretiskt plan är kollegial verbalisering. Metoden går ut på att filma operatörer i arbete och be dem verbalisera, alltså berätta, vad de gör. Filmen visas sedan för den filmade operatörnes kollegor och kollegorna får nu ge sin version av vad kollegan gör och hur de tänker att denne resonerar i arbetssituationen.

Som nämndes ovan är kunskap något personligt och ofta svårt att uttrycka. Även om kunskap är personlig så är den grundad och utvecklad i interaktion med miljön, detta innebär att individer som befunnit sig i samma miljö utvecklar liknande kontexter. Det gör att kollegor kan tyda varandras målmedvetna handlingar och med något olika erfarenheter kommer deras utsagor att variera något men på det stora hela kommer det finnas mycket överlapp. Därmed kan dessa oberoende utsagor användas för att bättre förstå strukturen på miljön som dessa individer arbetar i, samt klargöra vad som ligger till grund för deras beslutsfattande.

Tesen som jag alltså driver i denna avhandling är att elicitering inte är en extraktionsprocess. Majoriteten av den kunskap en individ besitter grundar sig i tyst kunskap men gör sig synlig i målmedvetet agerande i miljön. Kunskapselicitering ska därmed istället ses som en metod där experter observeras i kontext-inducerande miljöer och där expertens målmedvetna beteenden dokumenteras. Metoden är behjälplig för forskare att identifiera potentiella förbättringar i informationsteknologiska miljöer.

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