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Cognitive Work Analysis: Foundations, Extensions, and Challenges

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ABSTRACT

This essay, which reviews the foundations, extensions, and challenges of cognitive work analysis, is based on a keynote address delivered at the 10th International Naturalistic Decision Making Conference held in Orlando, Florida from 31 May to 3 June, 2011. It describes the origins of cognitive work analysis and the utility of this framework for designing ecological interfaces, as well as for tackling a variety of other design challenges, particularly, the design of teams or organisations. Also featured in this essay is the formulation of a methodological perspective of cognitive work analysis, which complements the conceptual accounts provided by Rasmussen (1986), Rasmussen, Pejtersen, and Goodstein (1994), and Vicente (1999). Finally, this essay highlights the latest shift in research emphasis from work domain analysis, the first dimension of cognitive work analysis, to the subsequent dimensions of this framework.

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Executive Summary

Workers in complex sociotechnical systems, such as military systems, have incredibly challenging jobs. To help them perform their jobs effectively, it is indisputable that first we need to understand the nature of their work. Only then is it possible to design interfaces, teams, or training systems, for instance, that will enable workers to meet their work demands successfully – in a way that is safe, productive, and healthy (Vicente, 1999).

This essay, which is based on a keynote address delivered at the 10th International Naturalistic Decision Making Conference held in Orlando, Florida from 31 May to 3 June, 2011, reviews the foundations, extensions, and challenges of cognitive work analysis, a framework for the analysis, design and evaluation of work in complex sociotechnical systems (Rasmussen, 1986; Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999). This framework comprises five dimensions of analysis, namely, work domain analysis, control task analysis, strategies analysis, social organisation and cooperation analysis, and worker competencies analysis. Each dimension is concerned with the analysis of particular types of constraints on actors' behaviour. Within these constraints, actors have many possibilities for action. By focusing on the analysis of constraints, rather than specific instances of behaviour, cognitive work analysis promotes designing for adaptation.

This essay demonstrates that there have been substantial research outcomes in cognitive work analysis over the last few decades. Included in these achievements is the development of the cognitive work analysis framework itself, which has its origins in the work of Jens Rasmussen and his colleagues at the Risø National Laboratory in Denmark. Based on empirical studies of how work is achieved in naturalistic settings, these researchers conceptualised a solid foundation for work analysis.

Subsequently, some of the concepts of cognitive work analysis were extended into ecological interface design (EID), a framework for designing interfaces for complex sociotechnical systems (Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1990, 1992). Unlike other approaches to interface design, the EID framework has been subjected to a comprehensive program of controlled experimental investigations. These investigations have demonstrated that EID can lead to better performance than existing interfaces for many types of systems, including military ones. The EID program has addressed in part some of the limitations of the original research by the Risø group, which relate to the lack of experimental testing of the concepts of cognitive work analysis and the generalisability of these concepts to a variety of systems. Future research on EID will include extensions to this framework to incorporate, among other things, additional concepts of cognitive work analysis and other work analysis techniques.

Novel applications of cognitive work analysis, to problems other than interface design, have been achieved largely in industrial settings. These applications include the evaluation of system design concepts, the definition of training needs and training-system requirements, and the development of new team or organisational designs. Some of these applications have required extensions to the basic concepts of cognitive work analysis. While these applications have had an impact in industrial settings, and have made a unique contribution to design relative to standard techniques, empirical evaluation is lacking. For this to be achieved, a shift to a research setting may be necessary.

The methodological program on cognitive work analysis complements the seminal monographs by Rasmussen (1986), Rasmussen et al. (1994), and Vicente (1999), which provide a comprehensive conceptual perspective of this framework. This program recognises that the widespread adoption of cognitive work analysis is hampered by the fact that this technique for work analysis is challenging, not only to learn, but also to perform *well*. While a substantive start has been made on methodology, much more work is necessary, especially in relation to the dimensions subsequent to work domain analysis.

The future program on the subsequent dimensions will echo the historical development of cognitive work analysis by building on the research of a range of communities. Given its complexity, it is improbable that the nature of human work in sociotechnical systems can be properly studied or understood by any one discipline or community. By contributing carefully investigated and detailed insights into diverse aspects of human work, multiple communities can provide valuable leverage points for cognitive work analysis. A significant challenge for researchers will be to build on any insights in a way that remains faithful to the theoretical underpinnings of cognitive work analysis, which appears to offer a powerful approach to design.

The preceding achievements in cognitive work analysis are likely to spark significant interest in this framework over the next decade. An immediate outcome of the growing popularity of this framework will be a proliferation of applications of cognitive work analysis, including many novel applications. This situation will emphasise one of the biggest challenges of cognitive work analysis, specifically, to support an integrated approach to *system* design.

Designing for adaptation is a complex problem that will not be resolved in a piecemeal fashion. It will not be resolved by just an ecological interface (Vicente, 1999) or just a team design, for instance. Instead, all elements of a system's design must be systematically integrated in a way that explicitly supports this objective, which raises theoretical, methodological, and practical challenges. I believe that cognitive work analysis has the potential to meet these challenges, but the task will not be simple.

References

Rasmussen, J. (1986). *Information processing and human-machine interaction: An approach to cognitive engineering*. New York: North-Holland.

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive systems engineering*. New York: John Wiley & Sons.

Vicente, K. J. (1999). *Cognitive work analysis: Toward safe, productive, and healthy computer-based work*. Mahwah, NJ: Lawrence Erlbaum Associates.

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Neelam is the lead scientist at the Centre for Cognitive Work and Safety Analysis. She joined the Defence Science and Technology Organisation (DSTO) as a Research Scientist in 1996 and was promoted to Senior Research Scientist in 1999. Some of her major projects have involved the extension of Cognitive Work Analysis to support the acquisition of complex, military systems and the application of AcciMap Analysis and the Critical Decision Method to enhance safety in these systems. Her current research interests include the development of theories and methods for analysing cognitive work in complex sociotechnical systems. Neelam obtained a BSc (Hons) in Psychology from the University of New South Wales, Australia in 1993 and a PhD in Psychology from the University of Auckland, New Zealand in 1996. She is a member of the Editorial Boards for the International Journal of Aviation Psychology and the Cognitive Engineering and Decision Making journal, and she is soon to publish a book on Work Domain Analysis.

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1. Introduction

A quarter of a century has passed since Jens Rasmussen published his first seminal monograph on cognitive work analysis (Rasmussen, 1986). More than a decade has slipped by since Kim Vicente's influential account of the same topic was published (Vicente, 1999). The 10th anniversary of the Naturalistic Decision Making Conference[1] seemed a fitting occasion to review the foundations of cognitive work analysis, to examine what has been achieved in this area of research, particularly over the last decade, and to consider what challenges remain to be addressed in the future. Some may question, quite rightfully, whether it is appropriate to focus on cognitive work analysis at a conference of the naturalistic decision making community. After all, don't those in this community mainly use cognitive *task* analysis methods? While this is most likely true, the reason I am convinced of its appropriateness is that cognitive work analysis is based on naturalistic observation. Cognitive work analysis was developed in keeping with observations of how work is achieved in the real world. This theme underpins this essay on the foundations, extensions, and challenges of cognitive work analysis.

2. Why Work Analysis?

It is quite safe to assume, I imagine, that none in the naturalistic decision making community would doubt the importance of work analysis; by *work analysis* I mean any technique or approach for analysing work or tasks. It is unquestionable that jobs in complex sociotechnical systems, such as hospitals, military aviation, and emergency management organisations, are highly challenging. It also follows logically that to support workers in these demanding roles, it is first necessary to understand the nature of their work. Only then is it possible to create designs of interfaces, teams, or training systems, for example, that will enable workers to meet their work demands successfully – in a way that is safe, productive, and healthy (Vicente, 1999).

There are countless techniques for work analysis, too numerous to mention here. Hierarchical task analysis (e.g., Shepherd, 2001), cognitive task analysis (e.g., Schraagen, Chipman & Shalin, 2000), and cognitive work analysis are some well known ones. In this essay, I focus on just one of these techniques, specifically, cognitive work analysis. This framework is particularly well suited for the analysis, design, and evaluation of work in complex sociotechnical systems.

3. What is Cognitive Work Analysis?

Cognitive work analysis is a framework that defines the work demands of complex sociotechnical systems in terms of the constraints on actors (Rasmussen, 1986; Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999). Many different disciplines use the term *constraints*. For example, this term features in the language of mathematicians and engineers.

[1] This essay is based on a keynote address delivered at the 10th International Naturalistic Decision Making Conference, Orlando, FL, May 31 – June 3, 2011.

However, this term has different meanings in different contexts. In the case of cognitive work analysis, *constraints* are limits on behaviour, which must be respected by actors for a system to perform effectively (Figure 1). Constraints distinguish behaviours that are possible or acceptable from those that are impossible or unacceptable. Cognitive work analysis, therefore, is concerned with constraints that are "behavior-shaping" (Rasmussen et al., 1994, p. 25).

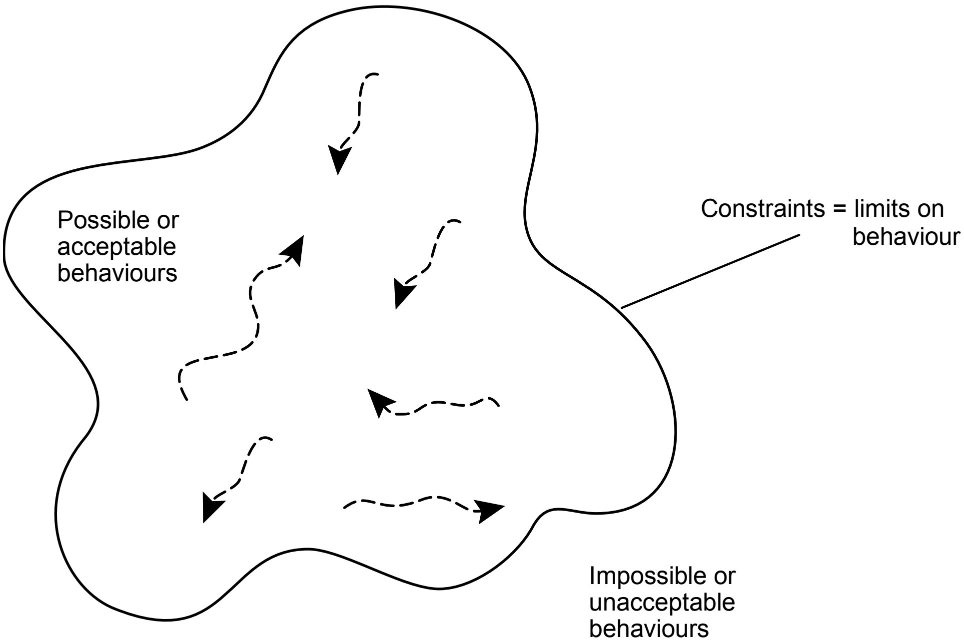

Figure 1 Constraints place limits on behaviour but still afford actors many possibilities for action

Although constraints place limits on behaviour, actors still have many options or possibilities for action, as indicated by the trajectories (arrows) in the centre of Figure 1. For instance, there are many different sequences in which actors can execute tasks or many different strategies that actors can use for decision making, while remaining within the boundaries of effective performance.

To offer a simple illustration, a system's purposes and physical resources place constraints on actors' behaviour. It will always be unacceptable to engage in actions that are inconsistent with a system's purposes and it will always be impossible to use physical resources to perform behaviours they do not have the functionality to support. Nevertheless, within those constraints, actors still have many possibilities for action that are compatible with a system's purposes and physical resources.

Complex sociotechnical systems can impose several kinds of constraints on actors. Accordingly, cognitive work analysis comprises a number of dimensions of analysis, which focus on different types of constraints (Table 1). Work domain analysis focuses on constraints imposed by the physical, social, or cultural environment of actors, which include a system's purposes and physical resources. Control task analysis is concerned with constraints imposed by the activity that is necessary in a system. Strategies analysis focuses on constraints imposed by the strategies for performing an activity. Social organisation and cooperation analysis concentrates on constraints associated with the organisation of work in a system. Finally, worker competencies analysis is concerned with constraints associated with human cognitive capabilities and limitations. Each dimension of cognitive work analysis has special tools for modelling these constraints.

Table 1 The dimensions of cognitive work analysis

Dimension	Constraints	Modelling Tools
Work domain analysis	Physical, social, or cultural environment, including purposes & physical resources	Abstraction-decomposition space, abstraction hierarchy
Control task analysis	Work situations, work functions, or control tasks	Decision ladder
Strategies analysis	Strategies	Information flow map
Social organisation & cooperation analysis	Allocation, distribution, or coordination of work	All of the above
Worker competencies analysis	Human cognitive capabilities and limitations	Skills, rules, and knowledge taxonomy

Figure 2 shows that the dimensions of cognitive work analysis collectively define a constraint-based space, within which actors have many possibilities for action. By focusing on constraints, cognitive work analysis promotes *designing for adaptation*. Rather than developing designs that support workers in particular ways of working, which have been prescribed or described by analysts in advance, the aim is to create designs that support workers in adapting their behaviour as they see fit without violating the system's constraints. With such designs, workers can create innovative patterns of behaviour, which may be particularly important for dealing with unforeseen events, or they can adopt ways of working that suit their individual preferences, while all the time remaining within the boundaries of effective performance.

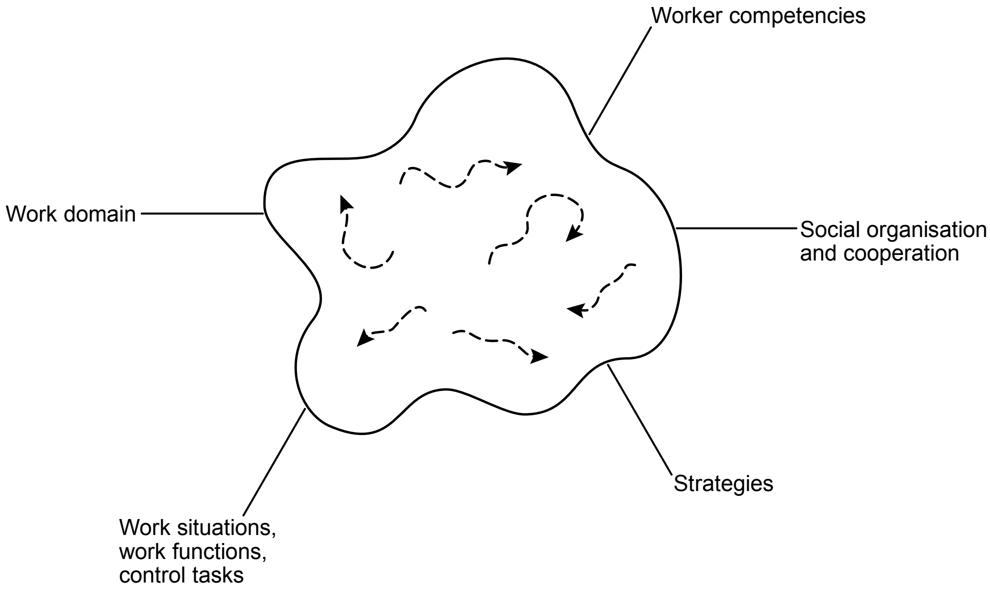

Figure 2 *The dimensions of cognitive work analysis collectively define a constraint-based space within which actors have many degrees of freedom for action.*

4. Foundations of Cognitive Work Analysis

The cognitive work analysis framework was developed in the 1960s and 1970s (Figure 3). It grew out of a research program at the Electronics Department of Risø National Laboratory in Denmark, headed by Jens Rasmussen. The aim of the Risø organisation at the time was to conduct research in support of the implementation of nuclear power in Denmark. In this section, an abbreviated history of the development of cognitive work analysis, based on scientific publications, is provided. Vicente (1999, 2001) offers a more comprehensive review.

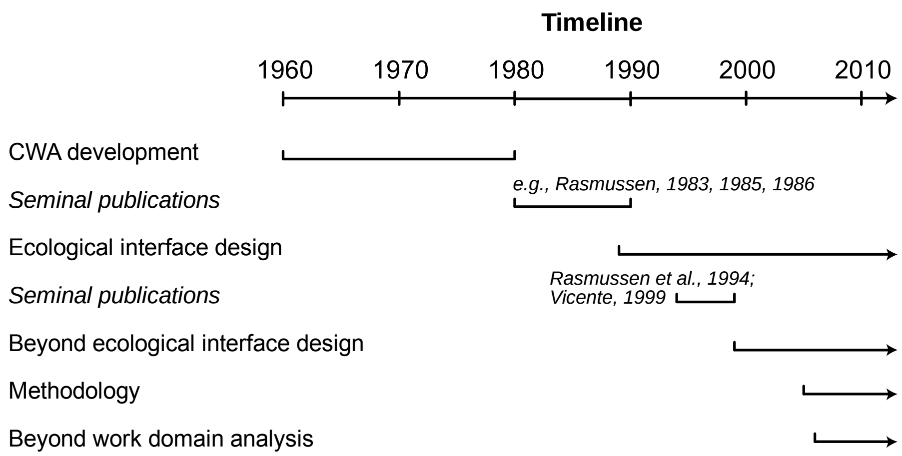

Figure 3 *Timeline for key theoretical developments in cognitive work analysis*

In the early 1960s, the focus of Rasmussen's group was on analysing the reliability of nuclear reactor equipment and instrumentation (Jensen, Rasmussen & Timmerman, 1963; Rasmussen & Timmerman, 1962). That is, they were concerned with *hardware reliability*. However, on the basis of empirical data collected in their research facilities, they found that although they could design hardware systems with extremely high reliability, accidents still occurred.

To try to understand why this was the case, an analysis of industrial accidents was conducted (Rasmussen, 1968a, 1968b, 1969). This study included 29 cases in the nuclear domain and 100 cases in the air transportation domain. The analysis revealed that human error accounted for approximately three quarters of these accidents. These errors arose when workers were confronted with unfamiliar situations that could not have been anticipated by designers. As these situations were unpredictable, workers could not have been given pre-planned procedures or instructions for how to manage them effectively. However, the analysis also showed that, in nearly all cases, workers could have handled these situations satisfactorily if the actual state of various aspects of the system at the time had been known to them. These findings highlighted the importance of designing to provide workers with information about the work domain, so they can adapt their behaviour to deal with the demands of a range of situations, including unforeseen events. It is worth noting that, more recently, others such as Perrow (1984), Reason (1990), and Leveson (1995) have also shown that accidents arise when workers are confronted with novel situations.

In the 1970s, the focus of the Risø group shifted from the study of machine reliability to human-machine reliability. Accordingly, these researchers conducted a number of empirical studies with the aim of establishing a sound basis for designing safer human-machine systems. Several of these studies led to conceptual developments, which were ultimately integrated into the cognitive work analysis framework. In what follows, I describe one of the studies that contributed to the concepts and modelling tools of work domain analysis, the first dimension of this framework. This was a field study of electronic troubleshooting.

In this field study, Rasmussen and Jensen (1973) chose to investigate the way in which professional technicians troubleshoot faults in electronic equipment. (This was not a surprising choice given that these researchers were from an electronics department.) Some of the aims of their research were to examine the problem-solving strategies of workers and to investigate the structure (i.e., event-independent properties) of the system that was the object of their activities. This research would contribute to establishing how the system can be represented in a model that is both compatible with human problem-solving and event-independent. With such a work domain model, workers should be able to reason about the system in a wide range of situations, including unforeseen events, and thus deal with these situations more effectively.

The field study included eight different types of instruments, each with a particular fault, and six professional technicians. The investigation was based on verbal protocol methodology, so technicians were required to verbalise their problem-solving processes as they set about their troubleshooting tasks. A total of 45 cases were recorded and transcribed, although only 30 were subjected to detailed analysis.

The data analysis involved the development of a preliminary coding scheme, which was used to analyse the verbal protocols. The protocols were then reviewed to determine if the information in them was captured effectively by the coding scheme. Any discrepancies led to changes in the coding scheme until it stabilised. The verbal protocols were then analysed with the final coding scheme. Figure 4 shows some of the results of this process. Although the details are unclear, the illustrations provide a sense of the complexity of the analyses.

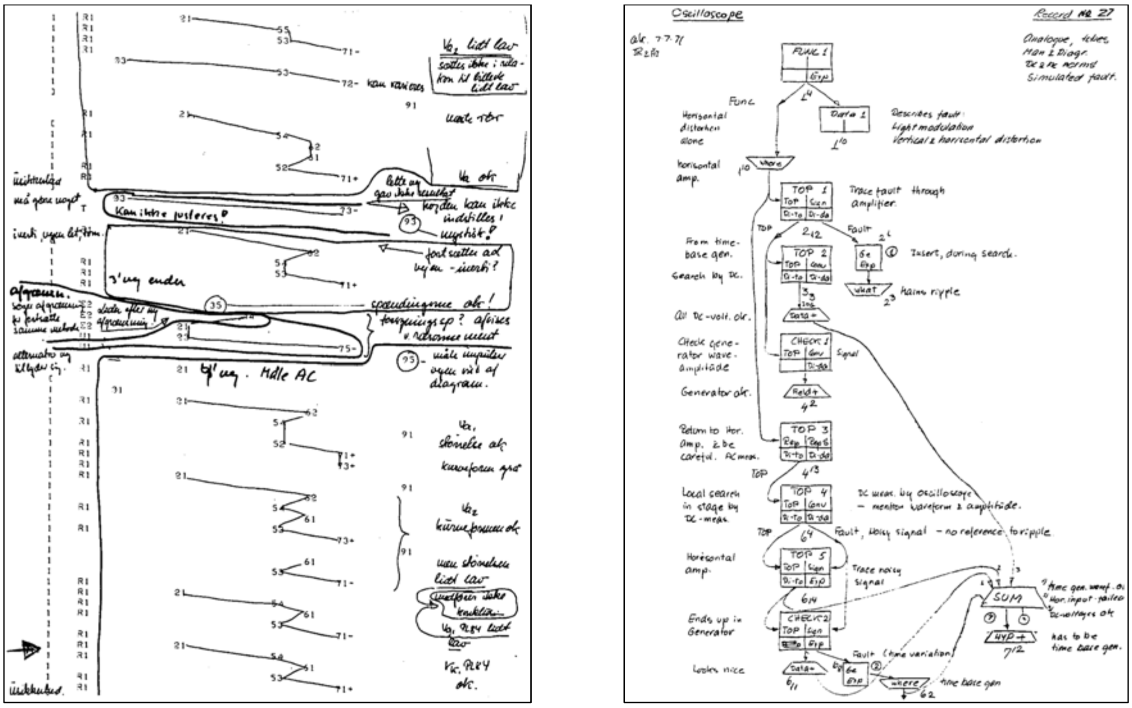

Figure 4 Illustrations of the analyses performed by Rasmussen and Jensen (1973), reproduced with permission

On the basis of the results of this study, a similar field study of a conventional power plant (Rasmussen, 1974), and investigations of problem solving by other researchers including Duncker (1945) and de Groot (1965), a number of patterns were identified in how workers reason about complex systems during problem solving in a range of situations (Figure 5). First, workers reason at different levels of *abstraction* while performing their jobs. Specifically, they spontaneously shift their view of a system from purposive concepts to physical concepts in order to match their task demands. Purposive concepts relate to information about a system's purposes whereas physical concepts relate to information about a system's physical resources.

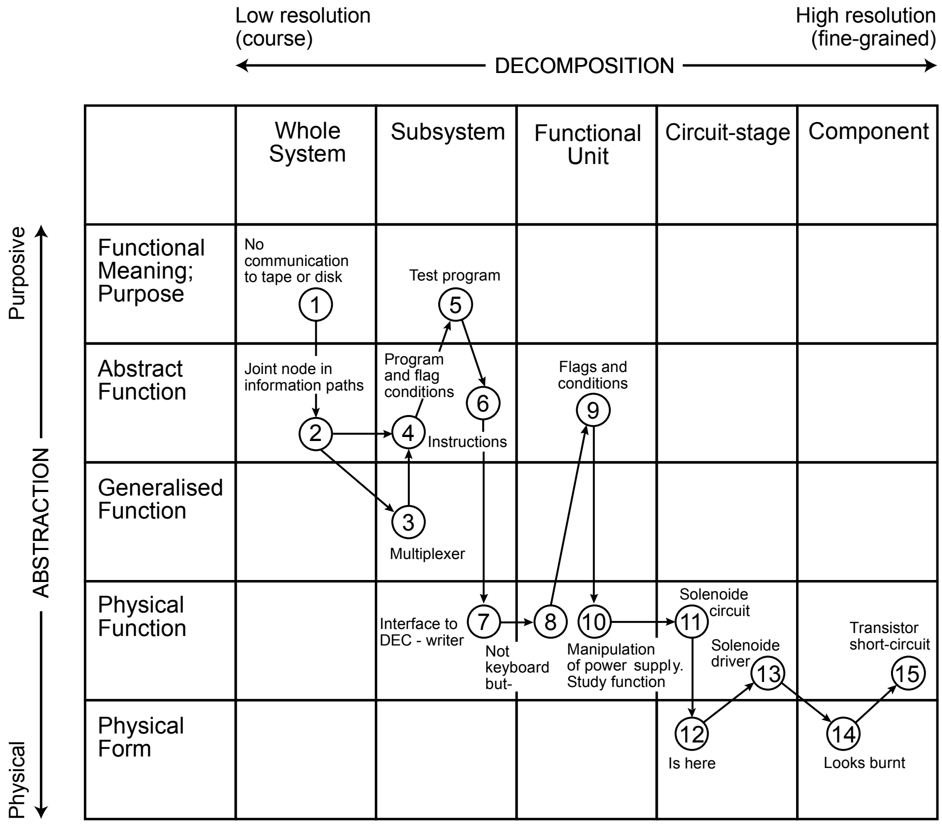

Figure 5 The abstraction-decomposition space. Reprinted and adapted from Advances in man-machine systems research, 4, *W. B. Rouse (Ed.), Rasmussen, J. A cognitive engineering approach to the modelling of decision making and its organization in: Process control, emergency management, CAD/CAM, office systems, and library systems (pp. 165-243), Copyright (1988) JAI Press, with permission from Elsevier.*

Second, workers reason at different levels of *decomposition* while performing their jobs. That is, they spontaneously shift their view of a system from coarse levels of resolution to fine-grained levels of resolution in order to match their task demands. The most coarse level of resolution relates to the whole system whereas the most fine-grained level relates to its components.

Third, when the conceptual lens with which workers view a system changes from purposive models to physical models, the level of resolution at which they view the system also changes from coarse models to fine-grained models. As a result, workers tend to adopt models along the diagonal of this reasoning space, which indicates that these models generally offer the most meaningful or useful views of a system. The numbered trajectory in Figure 5 shows the problem-solving path taken by an electronic technician in diagnosing faults in computer equipment.

Fourth, this reasoning space is event-independent. That is, although workers may adopt diverse problem-solving paths in the same situation, or unique problem-solving paths across a range of situations, all of these trajectories can be mapped onto, or can be explained by, this reasoning space.

Based on these findings, Rasmussen (1979, 1985) proposed the abstraction-decomposition space as a framework that can be used to represent complex systems in a way that is both consistent with the characteristics of human problem-solving and event-independent. Such a work domain model can support human reasoning about complex systems in a range of situations, including those that are novel or unforeseen.

Likewise, further empirical studies by the Risø group in the 1970s led to the other concepts and modelling tools of cognitive work analysis. These include the decision ladder for control task analysis, the information flow map for strategies analysis, and the skills, rules, and knowledge taxonomy for worker competencies analysis (Table 1). The abstraction-decomposition space, decision ladder, and information flow map are also applicable in social organisation and cooperation analysis.

In the 1980s, Rasmussen produced several seminal publications on cognitive work analysis (Figure 3). These included journal papers on the skills, rules, and knowledge taxonomy (Rasmussen, 1983) and the abstraction-decomposition space (Rasmussen, 1985). His first book (Rasmussen, 1986) followed.

Despite the achievements of the Risø program, there were some limitations of this research, as Vicente (2001) recognised. First, few of the concepts of cognitive work analysis, which were generated inductively from field studies, had been rigorously tested experimentally. Second, it was unclear whether these concepts were generalisable to systems other than those that led to their development. These limitations were addressed in part during the next major phase of research in the cognitive work analysis area, specifically, ecological interface design (Figure 3).

5. Ecological Interface Design

The ecological interface design (EID) framework formalises some of the concepts the Risø group had been using in designing interfaces for complex sociotechnical systems (Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1990, 1992). The primary aim of EID is to support worker adaptation to change and novelty. Its principle theoretical foundations are the abstraction-decomposition space and the skills, rules, and knowledge taxonomy.

To design an ecological interface, the abstraction-decomposition space is used to develop a model of a work domain, and thus define *what* information is necessary on a display to support human problem-solving in that system. The skills, rules, and knowledge taxonomy is used to define the form that information should take or *how* that information should be presented on a display.

To provide an example of a work domain model, Figure 6 shows an abstraction-decomposition space of the human body, developed by Hajdukiewicz (1998), which may be used to create an ecological interface for a surgical team. This model represents information about the human body at different levels of abstraction and decomposition, thereby defining the information content of a display.

	Whole Body	System	Organ	Tissue	Cell
Purposes	Homeostasis (Maintenance of Internal Environment)	Adequate Circulation, Blood Volume, Oxygenation, Ventilation	Adequate Organ Perfusion, Blood Flow	Adequate Tissue Oxygenation and Perfusion	
Balances	Balances: Mass and Energy Inflow, Storage, and Outflow	System Balances: Mass and Energy Inflow, Storage, Outflow, and Transfer	Organ Balances: Mass and Energy Inflow, Storage, Outflow, and Transfer	Tissue Balances: Mass and Energy Inflow, Storage, Outflow, and Transfer	
Processes	Total Volume of Body Fluid, Body Temperature, Supply: O_2, Fluids, Nutrients. Sink: CO_2, Fluids, Wastes	Circulation, Oxygenation, Ventilation, Circulating Volume	Perfusion Pressure, Organ Blood Flow, Vascular Resistance	Tissue Oxygenation, Respiration, Metabolism	Cell Metabolism, Chemical Reaction, Binding, Inflow, Outflow
Physiology			Organ Function	Tissue Function	Cellular Function
Anatomy			Organ Anatomy	Tissue Anatomy	Cellular Anatomy

Figure 6 An abstraction-decomposition space of the human body. Adapted from Hajdukiewicz (1998), with permission of the author.

The skills, rules, and knowledge taxonomy (Figure 7), which is used to define the form of information presentation, describes three qualitatively different ways in which people can interact with their environment. Briefly, skill-based behaviour involves highly automated and integrated patterns of action that are directly coupled to the environment in a continuous perception-action loop. Walking or steering a vehicle are examples of skill-based behaviour. Rule-based behaviour is defined by one-to-one associations between familiar perceptual cues in the environment and appropriate actions or intentions. Standard responses of drivers to traffic lights are examples of rule-based behaviour. Knowledge-based behaviour involves serial, analytical reasoning, or problem-solving, based on a symbolic mental representation of the relevant constraints in the environment. For example, knowledge-based behaviour is necessary for establishing the travel time to an unfamiliar destination based on such information as the distance between the start and end points, the traffic conditions at that time of day, and the mode or means of travel.

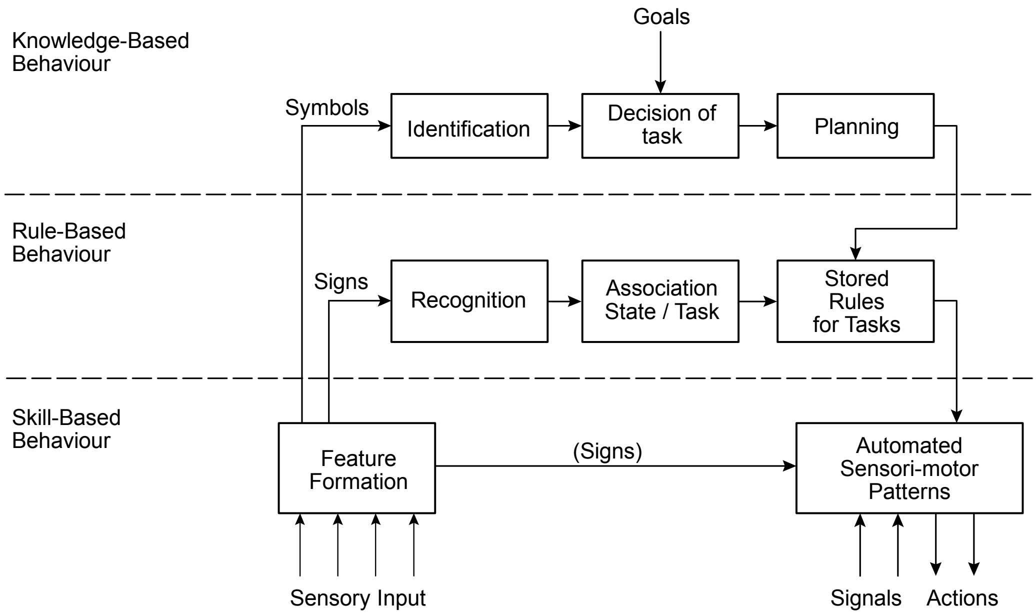

Figure 7 The skills, rules, and knowledge taxonomy. Adapted from Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. IEEE Transactions on Systems, Man, and Cybernetics, 13*(3), 257-266, (© 1983 IEEE), with permission.*

Motivated by the skills, rules, and knowledge taxonomy, the EID framework aims to present work domain information to workers in a form that encourages the use of skill-based and rule-based behaviour, because these are cognitively less demanding, while still providing support for knowledge-based behaviour, which is necessary for dealing with novel events. To achieve these aims, the EID framework comprises three design principles. To support skill-based behaviour, workers should be able to act directly on objects on the display. To facilitate rule-based behaviour, there should be a one-to-one mapping between work domain constraints and perceptual forms on the display. To support knowledge-based behaviour, the work domain should be presented in a form that preserves the information and relationships in the abstraction-decomposition space. This will serve as an externalised mental representation of work domain constraints to support adaptive problem solving.

5.1 Evaluation

Since the EID framework was developed, a great deal of research has been conducted in this area. In 2002, Vicente published a review of this body of work in which he discussed three criteria for assessing the EID framework. The *proof of principle* criterion simply assesses whether the EID framework can be applied to produce interfaces for complex sociotechnical systems. The *analytical* criterion assesses whether EID leads to new information requirements not found in existing interfaces. Lastly, the *empirical* criterion assesses whether EID actually leads to better performance compared with existing interfaces.

In this essay, I use these three criteria to summarise the value of the EID framework for designing interfaces for complex sociotechnical systems. This summary provides insight into the validity and generalisability of some of the concepts of cognitive work analysis, as established by experimental studies in EID. Accordingly, this summary demonstrates the contribution of the EID program to addressing some of the limitations of the original research by the Risø group, which were highlighted earlier. As the EID literature is vast, I discuss representative examples of studies that shed light on these questions, rather than providing a comprehensive review.

As shown in Table 2, several studies of EID across a range of systems have tested this framework against all three criteria, which was not the case when Vicente (2002) published his review. The shaded cells denote results obtained since that review. I should also note that, in all cases shown in this table, empirical evaluation means controlled experimental investigations.

Table 2 Studies of EID across a range of systems have obtained positive findings against proof of principle (P-of-P), analytical, and empirical criteria

System	Example Publications	P-of-P: Applied?	Analytical: New Info?	Empirical: Perform?
Process Control	Christoffersen, Hunter, & Vicente, 1996; Pawlak & Vicente, 1996	✓	✓	✓
Process Control	Reising & Sanderson, 1998, 2000a, 2000b	✓	✓	✓
Process Control	Ham & Yoon, 2001b	✓	✓	✓
Process Control	Jamieson, 2007	✓	✓	✓
Process Control	Lau, Jamieson, Skraaning Jr. & Burns, 2008	✓	✓	✓
Information Retrieval	Xu, Dainoff & Mark, 1999	✓	✓	✓
Medicine	Sharp & Helmicki, 1998	✓	✓	✓
Network Man.	Burns, Kuo & Ng, 2003	✓	✓	✓
Aviation	Borst, Suijkerbuijk, Mulder & van Paassen, 2006	✓	✓	✓
Military C&C	Bennett, Posey & Shattuck, 2008	✓	✓	✓

The table shows that a number of studies of EID in the context of process control systems have obtained positive findings against all three criteria. In other words, these studies show that EID can be applied to process control systems, that it does lead to new information requirements compared with existing interfaces for those systems, and that these new information requirements can lead to better performance by workers.

The initial studies by Vicente and his colleagues (e.g., Christoffersen et al., 1996; Pawlak & Vicente, 1996) were conducted with a process control microworld, as were the studies by Reising and Sanderson (e.g., 1998, 2000a, 2000b). Hence these studies examined the application of EID to process control systems in the context of relatively small-scale problems. Ham and Yoon's (2001b) work, however, which was conducted with a nuclear power plant secondary cooling system simulation, represented a medium-scale problem. More recently, Jamieson (2007) and Lau et al. (2008) have reported the application of EID to industrial-scale or large-scale problems in the petrochemical and nuclear power domains, respectively.

The studies listed in the last five rows of Table 2 examined the application of EID to medium-scale or large-scale problems in the context of systems other than process control. Positive results have been obtained against all three criteria for information retrieval and medical systems as well as network management, aviation, and military command and control systems. I should mention, however, that there are only one or two cases of empirical evaluation for each of these classes of systems. Nevertheless, collectively, the studies listed in Table 2 demonstrate that EID can be applied to a range of systems and that, for those systems, EID can uncover novel information requirements that lead to better performance, when compared with existing interfaces.

Three sets of experimental results are worth discussing in more detail. First, experimental studies show that EID generally leads to better performance than existing interfaces on non-routine or complex tasks, with no disadvantage on routine or simple tasks (e.g., Duez & Vicente, 2005; Ham & Yoon, 2001b; Lau et al., 2008; Pawlak & Vicente, 1996; Xu et al., 1999). This finding is consistent with the framework's emphasis on supporting workers in situations requiring adaptive problem-solving.

Second, experimental studies also show that the benefit of EID is due to its information content, not just its visual format (Ham & Yoon, 2001b; Xu et al., 1999). Specifically, when the visual format of ecological and existing interfaces is controlled, such that both present information in an alphanumeric format, for example, EID still leads to better performance.

Third, experimental studies have demonstrated that higher levels of abstraction and structural means-ends relations (i.e., links between information at different levels of abstraction) in the abstraction-decomposition space play a key role in the improved performance obtained with EID displays (e.g., Burns, 2000; Ham & Yoon, 2001a; Ham, Yoon & Han, 2008; Janzen & Vicente, 1998; Vicente, Christoffersen & Pereklita, 1995). Specifically, progressively adding information from higher levels of abstraction to an EID display leads to increasingly better levels of performance. In addition, grouping information according to structural means-ends relations leads to better performance with an EID display compared with not organising information in this way.

In summary, these findings all point to the value of the EID framework for designing interfaces to support worker adaptation in a variety of complex sociotechnical systems. Accordingly, this body of research provides experimental evidence for the validity of some of the concepts of cognitive work analysis as well as their generalisability to systems other than those that led to their development. Thus the EID program has gone quite some way in addressing the limitations of the original research by the Risø group.

5.2 Challenges

Several challenges remain to be addressed with the EID framework, as identified by those working in this area. First, further empirical evaluation of EID is still necessary for a range of systems.

Second, issues relating to sensor unavailability, noise, and failure must be resolved (e.g., Hajdukiewicz, Vicente, Doyle, Milgram, & Burns, 2001; Reising & Sanderson, 1998, 2002a, 2002b, 2004; Sharp & Helmicki, 1998; St-Cyr, 2006; St-Cyr & Vicente, 2004, 2005; Vicente & Rasmussen, 1992; Vicente, 2002). Specifically, the lack of availability of sensors in a system for obtaining all of the work domain information necessary for an EID display may compromise performance with such interfaces. In addition, the reliability of sensors with respect to noise and failure may compromise performance with EID displays.

Third, extensions to the EID framework may be necessary or beneficial for further improving performance with such displays. Burns (2000) has investigated supplementing EID with more specific design principles such as those relating to the problem of visual momentum described by Woods (1984). Watson and Sanderson (2007) have proposed extensions to EID to take advantage of the auditory modality for presenting information to workers instead of relying solely on visual displays. Jamieson, Miller, Ho, and Vicente (2007) and Miller and Vicente (2001) have investigated extending EID to take advantage of information requirements generated by other work analysis techniques, such as hierarchical task analysis, and other dimensions of cognitive work analysis, such as control task analysis.

Fourth, although there are a few cases of the adoption of EID displays by industry, significant technology transfer has yet to be achieved. A book by Burns and Hajdukiewicz (2004) on EID, which makes this framework more accessible to practitioners, may assist with facilitating this transfer.

Alongside the developments in EID, two other seminal monographs on cognitive work analysis were published in the 1990s by Rasmussen et al. (1994) and Vicente (1999), as indicated in Figure 3. Arguably, together with the experimental evidence in support of the EID framework and thus cognitive work analysis, these publications were contributory factors to the next major phase of research in this area, which extended the application of cognitive work analysis to problems other than interface design.

6. Beyond Ecological Interface Design

In the late 1990s and early in the next decade, cognitive work analysis was applied to a variety of problems including the definition of training needs and training-system requirements (Naikar & Sanderson, 1999), development of software specifications (Leveson, 2000), evaluation of system design concepts (Naikar & Sanderson, 2001), development of a team design (Naikar, Pearce, Drumm & Sanderson, 2003), definition of strategies for human error management (Naikar & Saunders, 2003), and development of recommendations for automation and role allocation (Bisantz, Roth, Brickman, Gosbee, Hettinger & McKinney, 2003). Unlike the program in ecological interface design, which has occurred largely within a research context, all of these applications of cognitive work analysis occurred in industrial settings or within a professional context. In what follows, I discuss the application of cognitive work analysis to one of these problems in more detail, specifically, team or organisational design.

6.1 Team/Organisational Design

For the problem of team or organisational design, the concepts of social organisation and cooperation analysis are particularly relevant (Naikar, 2006, in press). Like those of the other dimensions of cognitive work analysis, the concepts of this dimension are informed by studies of work in naturalistic settings. For example, the research of Rochlin, LaPorte, and Roberts (1987) on high reliability organisations is particularly relevant (Rasmussen et al., 1994; Vicente, 1999).

Rochlin et al. (1987) conducted a field study of how U.S. Navy personnel on aircraft carriers at sea coordinate their work activities. They found that the formal organisation of this system, that which is documented on paper, is rigid, hierarchical, and centralised, being characterised by clearly defined chains of command and means to enforce authority. Typically, this organisational structure governs operations on the ship.

During complex operations, however, a very different type of organisational structure is adopted. This organisational structure may be described as informal, given that it is not officially documented. The informal organisation is flat and distributed rather than hierarchical and centralised. For instance, workers at lower levels of the hierarchy have the autonomy to make critical decisions without the approval of those higher up. The informal organisation is also flexible in that there is no pre-specified plan for when it will be adopted. Furthermore, the specific organisational structure that is adopted on any one occasion is emergent, which in this case means that there is no simple or fixed mapping between people and roles and, therefore, no single informal organisational structure. Instead, the work organisation on the ship adapts to changes in circumstances. According to Rochlin et al. (1987), this adaptability contributes greatly to achieving the balance between the drive for safety and reliability and the drive for combat effectiveness.

So how are the concepts of cognitive work analysis in keeping with such observations of work organisation in naturalistic settings? Whereas Rasmussen et al. (1994) and Vicente (1999) focus on the implications of these observations for analysing, and thus supporting, existing organisational structures, I have also considered the implications of these observations for developing new team or organisational designs (Naikar, 2006, in press). The latter issue is what I emphasise in the following description of social organisation and cooperation analysis. Prior to doing so, I should mention that my ideas on this topic have not been formulated fully or tested completely. Therefore, in this part of the essay, I discuss a topic on which my colleagues and I are currently working.

Cognitive work analysis recognises that, in complex sociotechnical systems, flexible organisational structures that can be adapted to local contingencies are essential for dealing with a range of situations, including unanticipated events. Consequently, there is no attempt in this form of analysis to prescribe a single or best organisational structure. Instead, emphasis is placed on defining the set of possibilities for work organisation in a system, and developing a team or organisational design that can support or adopt those possibilities. By identifying the set of possibilities for work organisation in advance, it also becomes feasible to design interfaces, training systems, and other aids that are explicitly tailored to those possibilities, so that workers are provided with adequate support for adopting the range of possibilities. How, then, does one define the set of possibilities for work organisation in a system?

The first step is to identify the *criteria* that may shape or govern how work is allocated or distributed across actors in a range of situations. Rasmussen et al. (1994) and Vicente (1999) describe six criteria. Specifically, these are the competencies of actors, the access that actors have to information or the means for action, the requirements for minimising coordination or communication, the necessity for workload sharing, the requirements for safety and reliability, and the requirements for compliance (with regulations, for example). Presumably, different or additional criteria may be applicable depending on the system of interest.

Having identified the criteria that are relevant to a system, the next step is to examine how the work demands of the system may be allocated or distributed across actors as a function of applying various criteria; the criteria may be applied singly or in different combinations. To perform this step, representations of a system's work demands are necessary. The work demands of a system may be modelled in terms of the work domain, work situations, work functions, control tasks, or strategies (Table 1). Hence the modelling tools from the preceding dimensions of cognitive work analysis are relevant.

Figure 8 illustrates how a decision ladder model of an uninhabited aerial vehicle for maritime surveillance (Elix & Naikar, 2008) may be used to examine the distribution of control tasks across actors. Given certain criteria, such as the necessity for workload sharing or the competencies of actors, the shaded areas of the decision ladder might be allocated to Actor A and the remaining areas to Actor B. This representation, then, highlights the nature of the work content or responsibilities of the two actors, as well as their information, coordination, and resource requirements, given that work content. This figure represents one possibility for work organisation in the system. The application of other criteria may result in different possibilities (e.g., Figure 9).

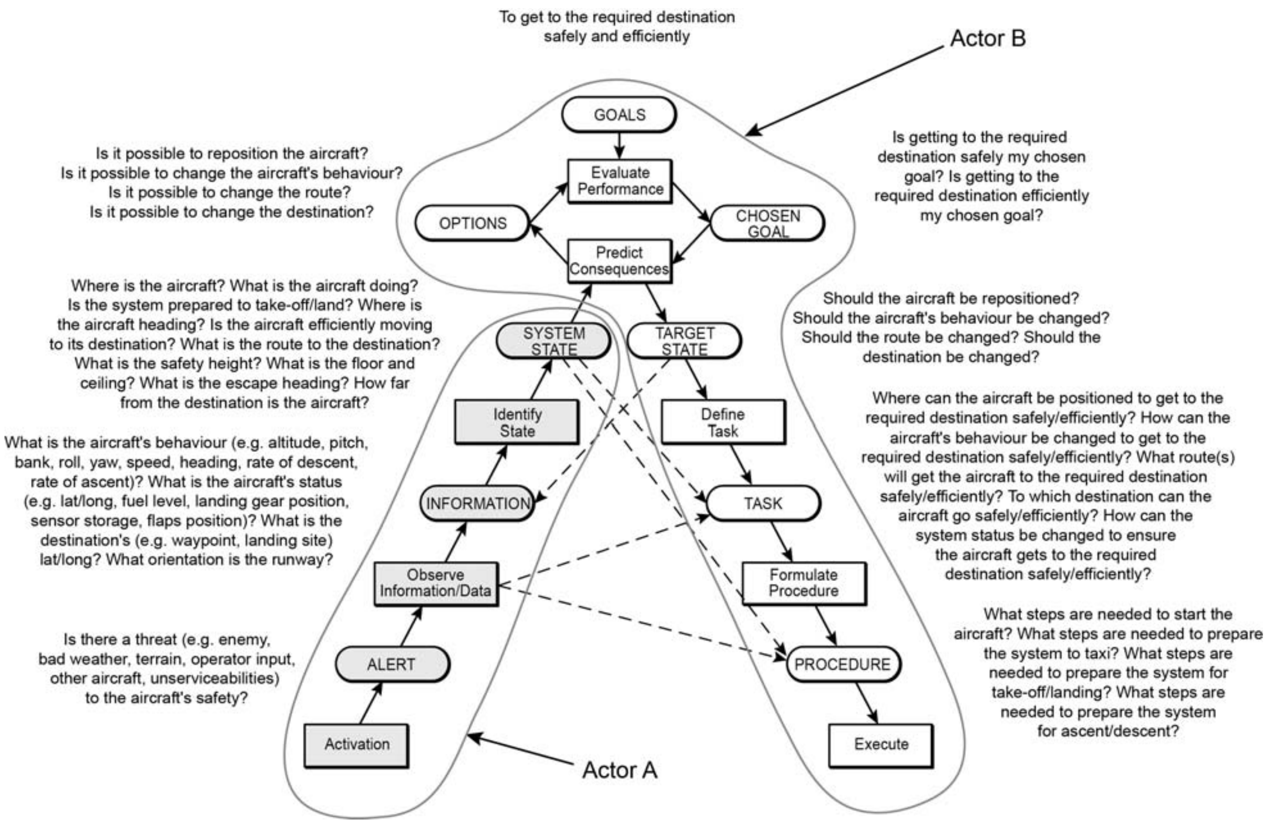

Figure 8 Use of the decision ladder to represent one possibility for work organisation in an uninhabited aerial vehicle for maritime surveillance

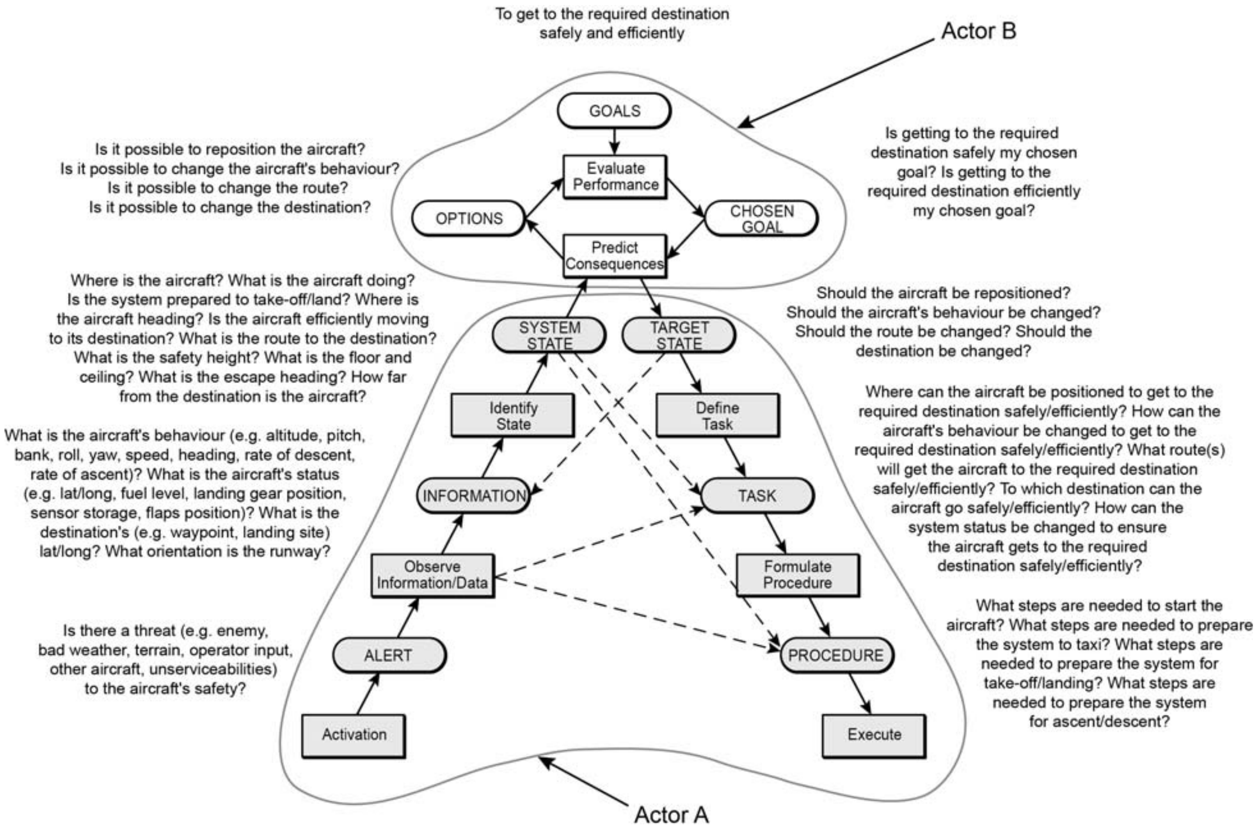

Figure 9 Use of the decision ladder to represent a second possibility for work organisation in an uninhabited aerial vehicle for maritime surveillance

The other modelling tools of cognitive work analysis may be used in a similar fashion to examine the possibilities for work organisation in a system. To offer another example, Figure 10 shows how an information flow map from strategies analysis may be used to examine the distribution of work across actors. In this figure, some aspects of a strategy for electronic troubleshooting are allocated to Actor A and other aspects to Actor B. (A more detailed description of this strategy is provided later in the section on strategies analysis.) I note that although I have used a single decision ladder and information flow map for illustration in this section, for most complex sociotechnical systems, multiple decision ladders and information flows maps are likely to be necessary for modelling work demands.

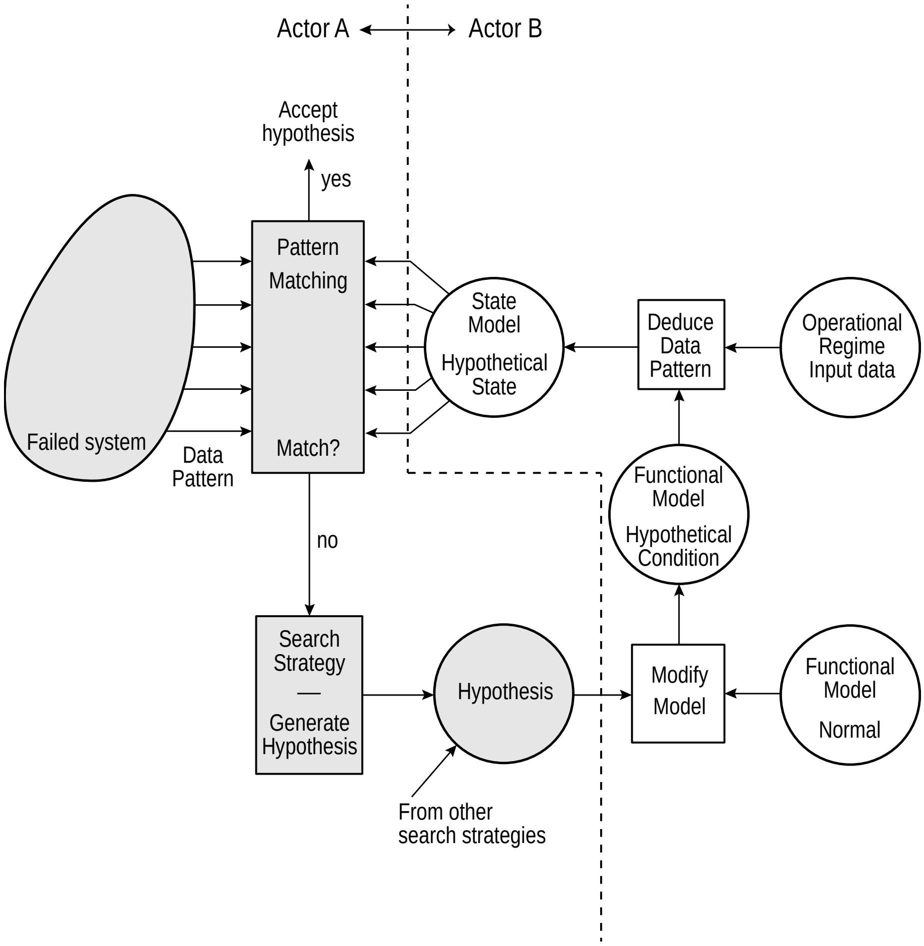

Figure 10 Use of an information flow map to examine the possibilities for work organisation in an electronic troubleshooting system. Adapted from Rasmussen, J. (1981). Models of mental strategies in process plant diagnosis. In J. Rasmussen & W. B. Rouse (Eds.), Human detection and diagnosis of system failures *(pp. 241-258). © 1981 Plenum Press (Figure 4), with kind permission from Springer Science+Business Media B.V., incorporating modifications made by Vicente (1999).*

Having defined the set of possibilities for work organisation in a system, the next step is to identify the team or organisational design requirements necessary for supporting each possibility[2] (Figure 11). For example, the requirements may relate to the team size, hierarchical structure, subgroups, or roles required for supporting each possibility. Following that, a team or organisational design that best fulfils the set of requirements, or that best supports the range of possibilities for work organisation, may be created.

[2] Requirements relating to the design of interfaces, training systems, and other aids for supporting the possibilities may also be produced. Some of these requirements may be targeted at maximising the strengths or minimising the limitations of each possibility.

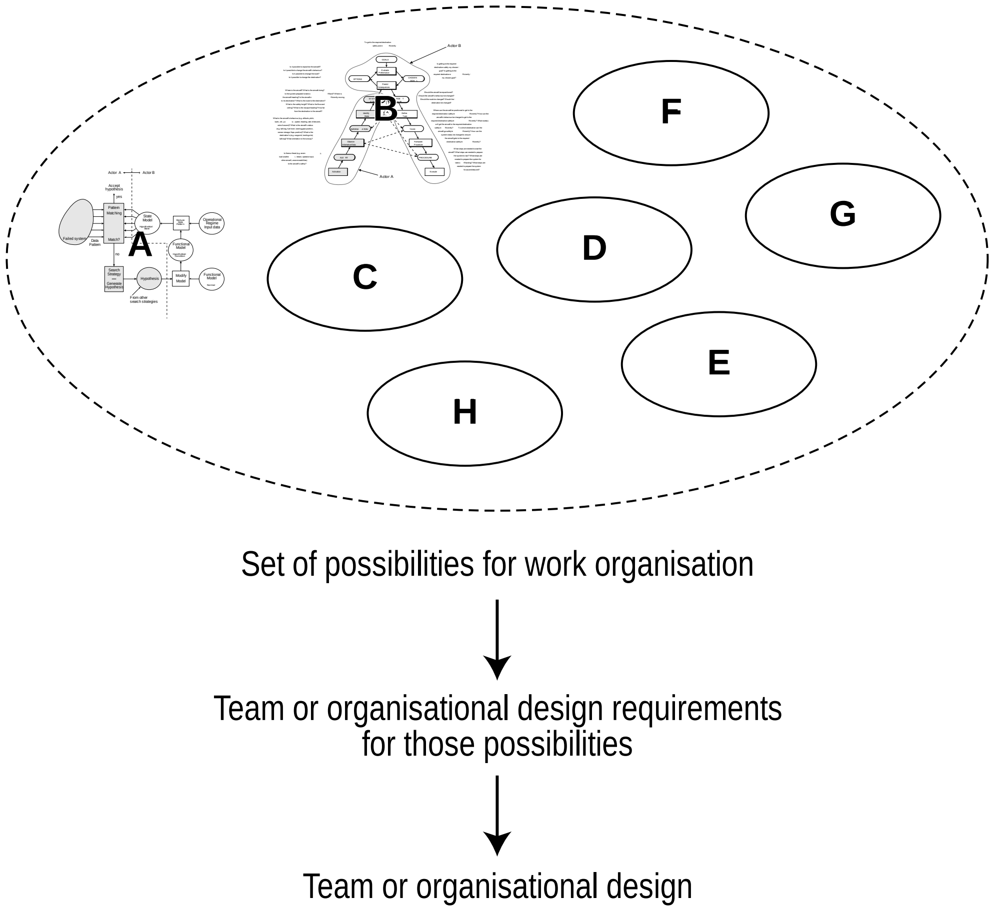

Figure 11 General process for creating a team or organisational design with cognitive work analysis

6.1.1 Application

Previously, we have used these concepts, albeit in a limited way, to develop a team design for a new Airborne Early Warning and Control system or AEW&C (Naikar, in press; Naikar et al., 2003). This team design, which was adopted by the Royal Australian Air Force, accommodates flexibility in the size of the team, the number of levels of hierarchy, and the roles or responsibilities of crew members.

Figure 12 shows an instantiation of the AEW&C team design in which the role of deputy mission commander is implemented when the mission commander needs to be buffered from administrative duties. On missions, or segments of missions, when this buffer is not required, the person in this role can assume other responsibilities or serve as a spare crew member to enable the rotation of crew through positions and thus allow more or longer rest periods for members of the team. These alternative configurations involve variations to team size, hierarchical structure, and roles or responsibilities.

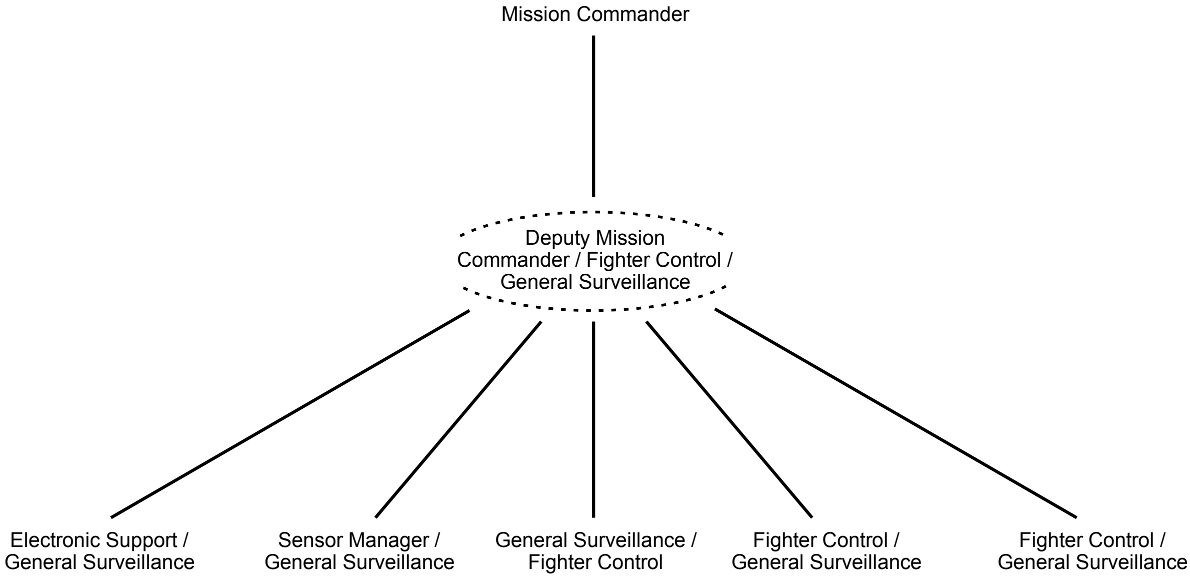

Figure 12 An instantiation of the team design for AEW&C

The specific process used to develop the team design for AEW&C has been reported in detail previously (Naikar, in press; Naikar et al., 2003). The approach to team or organisational design described in this essay builds on this process, particularly, by addressing its limitations. The details of this newly revised approach, as well as its strengths and limitations, are currently being investigated. Specifically, we are using this approach to develop team designs for operating inhabited and uninhabited vehicles for maritime surveillance (Elix & Naikar, 2011). In addition, we are using this approach to develop an organisational design for the Royal Australian Air Force (Treadwell, Yeung, Brady & Naikar, 2011). These case studies will add to the body of evidence on whether cognitive work analysis can be extended to develop new team or organisational designs for complex sociotechnical systems.

6.1.2 Challenges

One of the challenges we face in applying cognitive work analysis to problems like team or organisational design in industrial settings is empirical evaluation (Naikar, 2009, in press). It is important to acknowledge that we do not have empirical evidence that cognitive work analysis led to an effective team design for AEW&C or to a better team design for this system than other techniques might have. It is difficult, if not impossible, to conduct such studies in industrial settings because of time and resource constraints.

To illustrate, in order to establish empirically whether cognitive work analysis led to an effective team design for AEW&C, access to the real aircraft or mockups, prototypes, or simulations of relevant aspects of the aircraft are necessary. Such resources were not available when the team design for AEW&C was developed. At that time, AEW&C was a future system, which the Australian Government intended to acquire. It only existed as a concept – it had not been built or manufactured anywhere in the world. Thus there were no real aircraft, mockups, prototypes, or simulations. Another reason that empirical evaluation was not viable at that time is that AEW&C is a first-of-a-kind system. It incorporates significant advances in technology compared with what were then current-generation systems. Hence it was not possible to use existing systems to evaluate the team design for AEW&C.

When mockups, prototypes, or simulations of the aircraft become available, or when the real aircraft are brought into operation, there are other challenges with establishing whether cognitive work analysis led to an effective team design for AEW&C. The main difficulty is distinguishing the contribution of cognitive work analysis to the performance of the team design from other aspects of the aircraft's design, such as its interface design. For instance, if the team design performs well, it may be the case that the performance of the team is due to the interface design and that any team design would have performed well with that interface.

Similar challenges are faced in establishing whether cognitive work analysis led to a better team design for AEW&C than other techniques. Specifically, for this to be determined, it would be necessary to employ multiple techniques for team design and to compare the performance of the resulting designs using the real aircraft or suitable mockups, prototypes, or simulations. The time and resources necessary for such a study were not available on this project.

6.1.3 Evaluation

Such challenges with the empirical validation of techniques in industrial settings are not limited to cognitive work analysis. The challenges also apply to other techniques employed in industry, which is why these techniques are rarely evaluated formally. Instead, the techniques are assessed principally against the criterion of usefulness (Czaja, 1997; Whitefield, Wilson & Dowell, 1991; Vicente, 1999). Accordingly, I have evaluated applications of cognitive work analysis for the Australian Department of Defence against two measures of usefulness (Naikar, 2009, in press). The first is *impact* or the ability to influence practice on a project. The second is *uniqueness* or the ability to make a unique contribution to a project compared with techniques commonly used in industry. How, then, does the application of cognitive work analysis to design a team for AEW&C fare against these criteria?

There were two main demonstrations that cognitive work analysis had impact or influenced practice on this project. First, the team design that was developed for AEW&C was adopted by the Australian Defence Department. This team design was judged by subject matter experts to be suitable for AEW&C and better than other team designs they had considered. As it was not feasible to perform an empirical evaluation of this team design, the Defence Department implemented a number of strategies to manage the risk that it may be unsuitable for AEW&C. Second, on the basis of our analyses, the technical specifications for the aircraft were modified so that it better supported the team design for AEW&C. As this was done early in the acquisition cycle, prior to the signing of a contract with the aircraft manufacturer, the alterations were achieved without cost to the Australian Government.

Cognitive work analysis also made a unique contribution to this project because standard techniques for team design cannot readily be applied to future, first-of-a-kind systems. The standard techniques, which span a variety of disciplines including engineering, social and organisational psychology, and engineering psychology, differ markedly in their theoretical orientations to team design (Davis & Wacker, 1982, 1987; Hackman & Oldham, 1980; Lehner, 1991; Medsker & Campion, 1997; Sundstrom, De Meuse & Futrell, 1990). Nevertheless, all of the techniques depend on a work analysis of the system of interest.

Some of the techniques rely on studying or observing how work is done in a system in order to produce a team design for it. However, as future, first-of-a-kind systems are not functioning systems, and have no equivalent existing systems, the way in which work is done in these systems cannot be studied or observed. Other techniques rely on specifying how work should be done in a system in terms of a set of task sequences or procedures in order to create a team design for it. However, task sequences or procedures cannot be specified in full for future, first-of-a-kind systems because the details of their technical solutions are still largely undefined, workers often develop novel work practices as they gain experience with a new system, and workers may have to deal with unanticipated events, for which task sequences or procedures cannot be specified in advance.

In contrast to standard techniques for team design, cognitive work analysis is especially well suited to designing teams for future, first-of-a-kind systems. The analysis of the constraints on actors' behaviour does not require a functioning system. Moreover, these constraints can accommodate many different trajectories of behaviour, including task sequences or procedures that are difficult to specify a priori. Overall, then, as judged against the criteria of impact and uniqueness, cognitive work analysis appears to provide a useful approach for designing teams for future, first-of-a-kind systems.

Finally, it is worth considering briefly how applications of cognitive work analysis to problems other than interface design fare against the criteria outlined by Vicente (2002) for assessing the EID framework. Table 3 summarises the results of four projects conducted for the Australian Department of Defence. Without delving into the details of these projects, this table shows that the proof of principle and analytical criteria were satisfied in every case. (For comprehensive descriptions of these projects, see Naikar (2009, in press) or the original publications cited in Table 3.) That is, these projects demonstrated that cognitive work analysis can be applied to evaluate system design concepts, develop team designs, define training needs and training-system requirements, and define strategies for managing human error. Moreover, for each application, cognitive work analysis led to unique results compared with existing solutions or the results of other techniques. The empirical criterion, however, was not satisfied on any project due to time and resource constraints. A shift may be necessary from an industrial setting to a research setting for such studies to be conducted. Further case studies of these applications of cognitive work analysis across a range of systems, beyond just military ones, are also necessary.

Table 3 Assessment of four applications of cognitive work analysis to problems other than interface design against proof-of-principle (P-of-P), analytical, and empirical criteria

Application	Publication	P-of-P: Applied?	Analytical: New Results?	Empirical: Perform?
Evaluation of system design concepts	Naikar & Sanderson, 1999	✓	✓	
Team design	Naikar et al., 2003	✓	✓	
Training needs and training-system requirements	Naikar & Sanderson, 1999	✓	✓	
Human error management	Naikar & Saunders, 2003	✓	✓	

7. Methodology

Together with the results of the experimental program on EID, the outcomes of novel applications of cognitive work analysis in industrial settings are heartening. They suggest, among other things, that the more extensive use of cognitive work analysis for the analysis, design, and evaluation of work in sociotechnical systems may be fruitful. The widespread adoption of cognitive work analysis for this purpose, though, is hampered by the fact that this approach is challenging, not only to learn, but also to perform *well*. While the texts by Rasmussen et al. (1994) and Vicente (1999) have made cognitive work analysis much more accessible to analysts than it was previously, both texts focus on providing a conceptual perspective of this framework. As highlighted by Vicente (1999), this scope was a deliberate choice because cognitive work analysis was still relatively unknown at the time. Now, however, it is clear that the accessibility of cognitive work analysis may be improved further with the development of a complementary methodological perspective.

As shown in Figure 3, the development of a methodology for cognitive work analysis was the next major phase of research in this area. Although my colleagues and I have been conducting methodological research on several aspects of cognitive work analysis, in this essay I focus on my most recent research on work domain analysis (Naikar, in press). While the details of the methodology I have developed for work domain analysis are beyond the scope of this essay, I explain some of the challenges I encountered in its development, which conveys its scope.

7.1 Terminology

One challenge I faced was terminology. The terms used for naming and describing concepts, and whether these terms are defined unambiguously and employed consistently, have a significant effect on one's understanding of what work domain analysis is, and thus how it should be performed. Is there a difference between a *system* and a *work domain* for example? Can these terms be used interchangeably and, if not, what is the difference between them? In his book on cognitive work analysis, Vicente (1999) provides a reasonably comprehensive glossary. In developing a methodology for work domain analysis, my aim was to use terms in a way that was as consistent with this glossary as possible. There were instances, however, when I thought it justifiable to depart from the definitions provided in Vicente's glossary.

One example is the usage of the term *system*. This term is defined by Vicente (1999) as "A set of interrelated elements that share a common Goal or Purpose" (p. 9). He states that a system can be a sociotechnical system, work domain, or actor, whereby an actor is a worker or automation. This can be taken to mean that the term *system* may be used to refer to four very different concepts. Therefore, unless it is somehow made clear how the term *system* is being used whenever it is mentioned, there is much scope for creating misunderstanding of the concepts and methodology of cognitive work analysis.

For this reason, in discussing methodology for work domain analysis (Naikar, in press), I have elected to use the term *system* only when referring to a sociotechnical system, which Vicente (1999) defines as "A System composed of technical, psychological, and social elements" (p. 9). Admittedly, this is a somewhat arbitrary choice, but the bottom line is that appreciating the distinctions between the four concepts listed above is critical for understanding and performing work domain analysis. Using the term *system* to refer to all four of these concepts, or more than one concept, obscures these critical distinctions. In particular, a *work domain* is not the same thing as a *sociotechnical system*, but there are many instances when the term *system* is used to refer to both of these concepts and sometimes it is unclear which concept is under discussion.

Arguably, the most significant departure I have made from Vicente's (1999) glossary is the definition of the term *work domain*, not because Vicente's definition is incorrect, but because it can be misinterpreted. Vicente's definition is also limited in some respects given the range of systems and problems to which cognitive work analysis is now being applied. Vicente (1999) defines a *work domain* as "The System being controlled, independent of any particular Worker, Automation, Event, Task, Goal, or Interface" (p.10). This definition has been taken to mean, among other things, that a work domain model cannot include control systems such as automation (Miller, 2004; Miller & Sanderson, 2000). It is not clear to me that this is what Vicente intended. My interpretation of his work is that work domain models can include the structural properties, or relatively permanent properties, of control systems, but not their behaviour, which is consistent with the theoretical underpinnings of work domain analysis (Naikar, in press).

Nevertheless, because the issue of the representation of control systems in a work domain model is important for many systems and applications, and given that Vicente's (1999) definition has caused confusion on this and other similar points, I have defined the term *work domain* instead as the functional structure of the physical, social, or cultural environment of actors in a system, which places constraints on their behaviour (Naikar, in press). Following Vicente, I use the term *functional* to mean "action-relevant" (p.155) and the term *structure* to mean "A relatively permanent relational property of a System" (p.9).

My definition of *work domain* differs from Vicente's (1999) definition in emphasis more than in semantic content. The term *functional* in my definition is similar to the concept of the system being controlled in Vicente's definition. The main difference is that the concept of relevance for action can be more readily extended to a broader range of systems, particularly those in which the constraints on actors' behaviour originate in human intentions rather than in physical or natural laws. The term *structure*, which in my definition refers to a relatively permanent property of a system, is similar to Vicente's concept of independence from any particular worker, automation, event, task, goal or interface. However, my definition makes clearer that a work domain model can include the structural properties of objects in the environment of actors such as automation, for example. The term *environment* in my definition is consistent with Vicente's (1999) and Rasmussen et al.'s (1994) descriptions of the work domain as representing the environment, field, landscape, or territory in which workers operate. Such terms are more naturally associated with physical surroundings or conditions, but workers in sociotechnical systems operate within a social or cultural environment as well. Work domain analysis, then, is concerned with analysing the functional structure of the physical, social, or cultural environment of actors in a system, as all of these types of environments can place constraints on their behaviour.

7.2 Guidelines

A second challenge I faced was formulating guidelines for work domain analysis in a form that remains faithful to how this type of analysis is actually performed by experienced analysts, but still serves as an instructional tool for novices. Initially, the guidelines were presented as a series of steps (Naikar, Hopcroft & Moylan, 2005). However, as the process of performing work domain analysis is flexible and iterative, not fixed and linear, I reformulated the guidelines as a set of analytic themes or questions for analysts to consider when performing work domain analysis (Naikar, in press). These analytic themes (Figure 13), which are intertwined and difficult to separate in practice, represent the major concerns that analysts confront recurrently while performing a work domain analysis. Analysts may consider the analytic themes in any order and several analytic themes may be under deliberation at any one time. Thus the analytic themes may be visualised as bubbles that appear and disappear continually, in any order, either singly or several at a time.

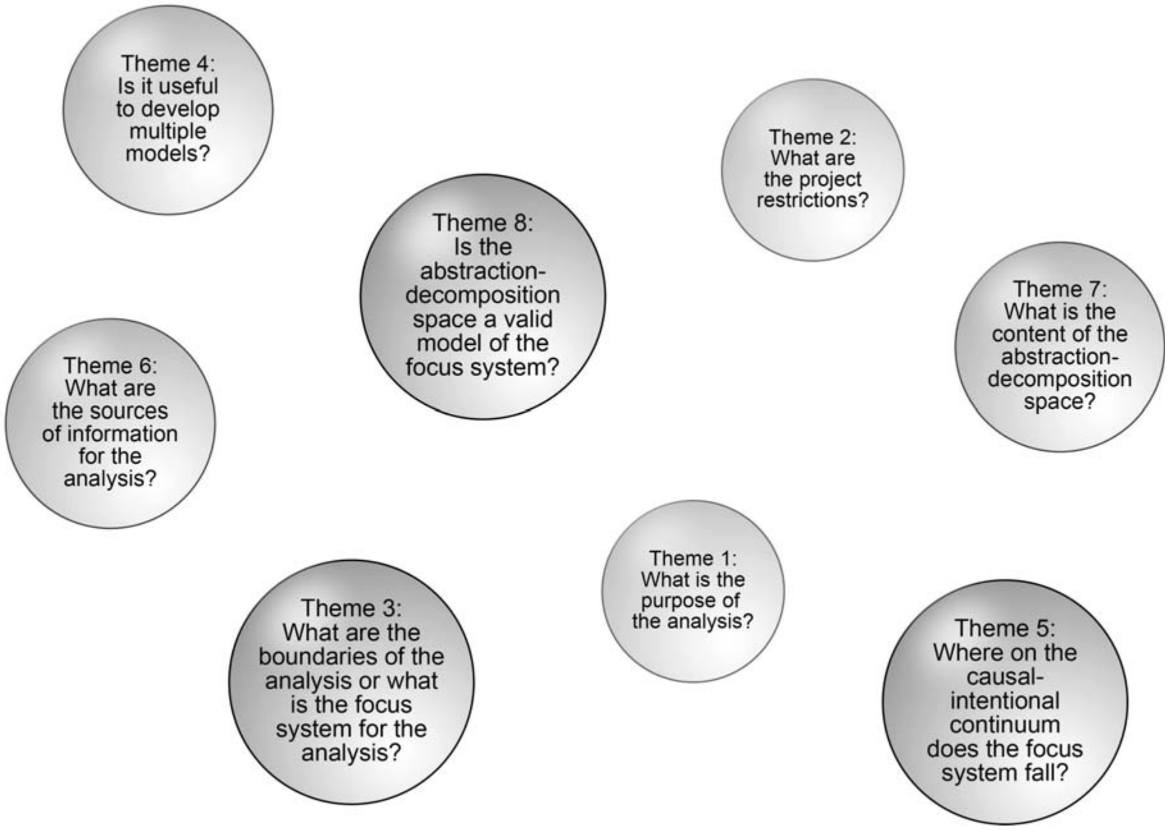

Figure 13   Analytic themes for work domain analysis

7.3 Multiple Models

In developing the guidelines, I avoided providing a personal account of how I perform work domain analysis. Instead, I reviewed hundreds of publications, produced by many different analysts, to establish the most powerful and useful ways of creating work domain models. This point may be illustrated in relation to the analytic theme *Is it Useful to Develop Multiple Models?*

One reason that analysts create multiple work domain models of a system is to represent different stakeholders' perspectives of a problem (Naikar, in press). *Stakeholders* may be described as individuals or groups with different views of a particular problem. The views or perspectives of stakeholders may be described as their *object worlds*. Stakeholders generally have something to gain or lose with respect to the problem under consideration, which means that they usually have to interact or coordinate their activities to achieve their respective objectives. By modelling the perspectives of multiple stakeholders, it becomes possible to introduce designs for one stakeholder without creating unintended side effects on other stakeholders. In addition, designs may be produced that allow stakeholders to coordinate their activities more effectively.

One example of multiple models of stakeholders' perspectives was developed by Burns and Vicente (2000) for an engineering design system (Figure 14). The stakeholders in this system were all concerned with the design of a control panel for the control room of a nuclear power plant. The stakeholders included human factors designers, structural engineers, implementers, the customer, and management. Each stakeholder had a different view or perspective of the design of the control panel. For instance, whereas human factors engineers were concerned with the comfort and usability of the design, structural engineers were concerned with designing a control panel with a certain strength and rigidity. This representation of multiple stakeholders' perspectives is typical of those produced by most researchers in that there is one work domain model for each stakeholder.

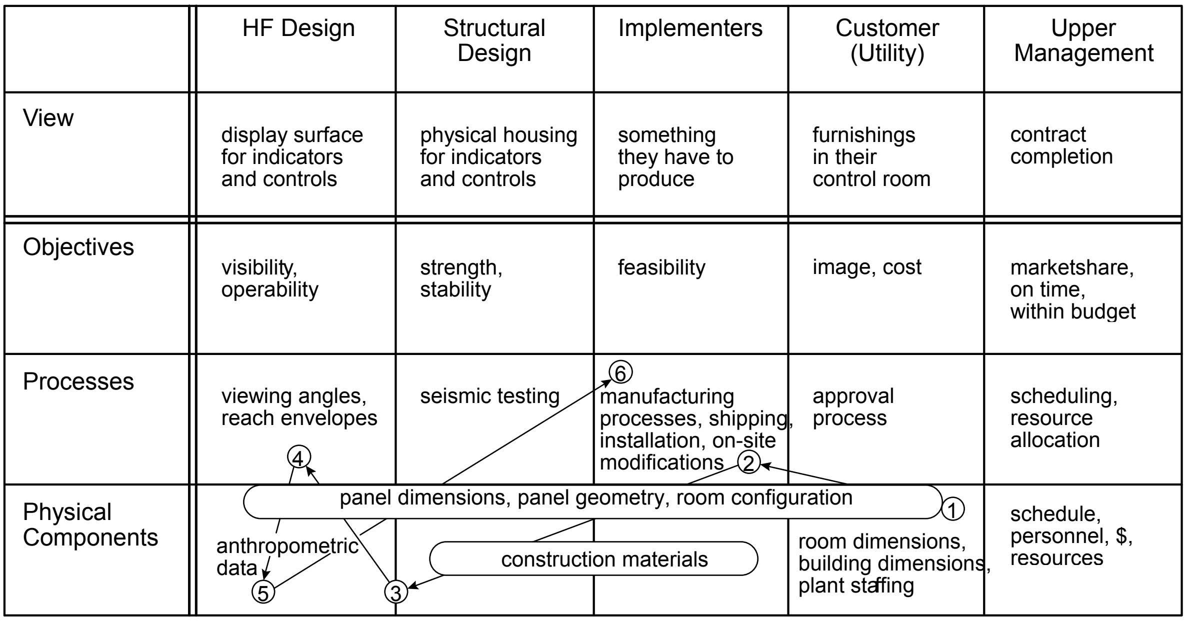

Figure 14 Multiple models of stakeholders in an engineering design system. From Burns, C. M., & Vicente, K. J., A framework for describing and understanding interdisciplinary interactions in design, Proceedings of DIS '95: Symposium on Designing Interactive Systems, *97-103, © ACM, Inc. http://doi.acm.org/10.1145/225434.225445. Reprinted by permission, incorporating modifications made by Vicente (1999).*

There is, however, one exception and that is a representation of multiple stakeholders' perspectives produced by Rasmussen, Pejtersen and Schmidt (1990) and Rasmussen et al. (1994) for the treatment of patients in a hospital (Table 4 and Figure 15). The important point to note about Table 4 is that none of the labels in the top row signify stakeholders. Instead, the labels signify work domains, independently of any stakeholders, that must be considered in the treatment of patients in a hospital. These work domains include a patient's private life and health as well as a hospital's cure, care, and administrative fields of interest.

Table 4 *Work domains that must be considered in the treatment of patients in a hospital. Adapted from Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P.* Cognitive systems engineering. *Copyright 1994 John Wiley & Sons. Reproduced with permission of John Wiley & Sons, Inc.*

	PATIENT		**HOSPITAL**		
	Private Life	Health	Cure	Care	Administration
Goals and Constraints	Working relations and conditions; Family relations; Goals and constraints of plans and commitments	Effects of illness and treatment on person's ability to meet subjective goals and criteria	Cure patient; Research, Training MDs; Public opinion; Legal, economic, and ethical constraints	Patient well being, physical and psychic care; Public opinion, economic and legal constraints	Laws and regulations of society, associa-tions and unions; Workers' protection regulations etc.
Priority Measures, Flow of Values and Material	Personal economy, Probability of unemployment, cure, etc.	Probability of cure, priority measures, pace versus side-effects, etc.	Categories of diseases: Cost of treatments, patient suffering, research relevance	Flow of patients according to category; Treatment, and load on staff and facilities	Distribution of funds on activities; Flow of material and personnel to diseases, departments
General Functions and Activities	Work functions; Family relations; Living conditions	State of health; Diseases and possible treatments	Cure, diagnostics, surgery, medication, etc. Research, clinical, experiments	Board and lodging; Hygiene; Social Care, Physical support, transportation, etc.	Personnel and material administration, Accounting, sales and purchase
Physical Activities in Work, Physical Processes of Equipment	Physical work activities, spare time and sports activities; Homework; Transportation, etc.	Specific organic disorders and possible treatment, Previous illness and cures	Specific research and treatment procedures; Use of tools and equipment	Monitoring, treating, moving, cleaning and serving patients; Psychic Care	Processes in the administrative functions. Office and planning procedures
Appearance, Location and Configuration of Material Objects	Patient identification, age, address, profession, education, family members, etc.	Physical state of patient, weight, height, previous treatments, etc.	Material resources, patients, personnel, equipment; Medicine, tools, etc.	Facilities and equipment in patient quarters, kitchens, etc. Inventory of linen, food, etc.	Inventory of employees, patients, buildings, equipment, etc.

Figure 15 maps the stakeholders who are concerned with the treatment of patients in a hospital onto the various work domain models. The stakeholders include a patient's general medical practitioner as well as a hospital's medical doctors, general manager, head nurses, nurses, and assistant nurses. This representation shows that a stakeholder may be concerned with more than one work domain. Nurses, for example, are concerned with the work domains of cure and care as well as administration. In addition, several stakeholders may be concerned with the same work domain, although with different but overlapping aspects. For example, all of the stakeholders on the right of Figure 15 are concerned with the work domain of care but they have different, yet overlapping, spheres of concern.

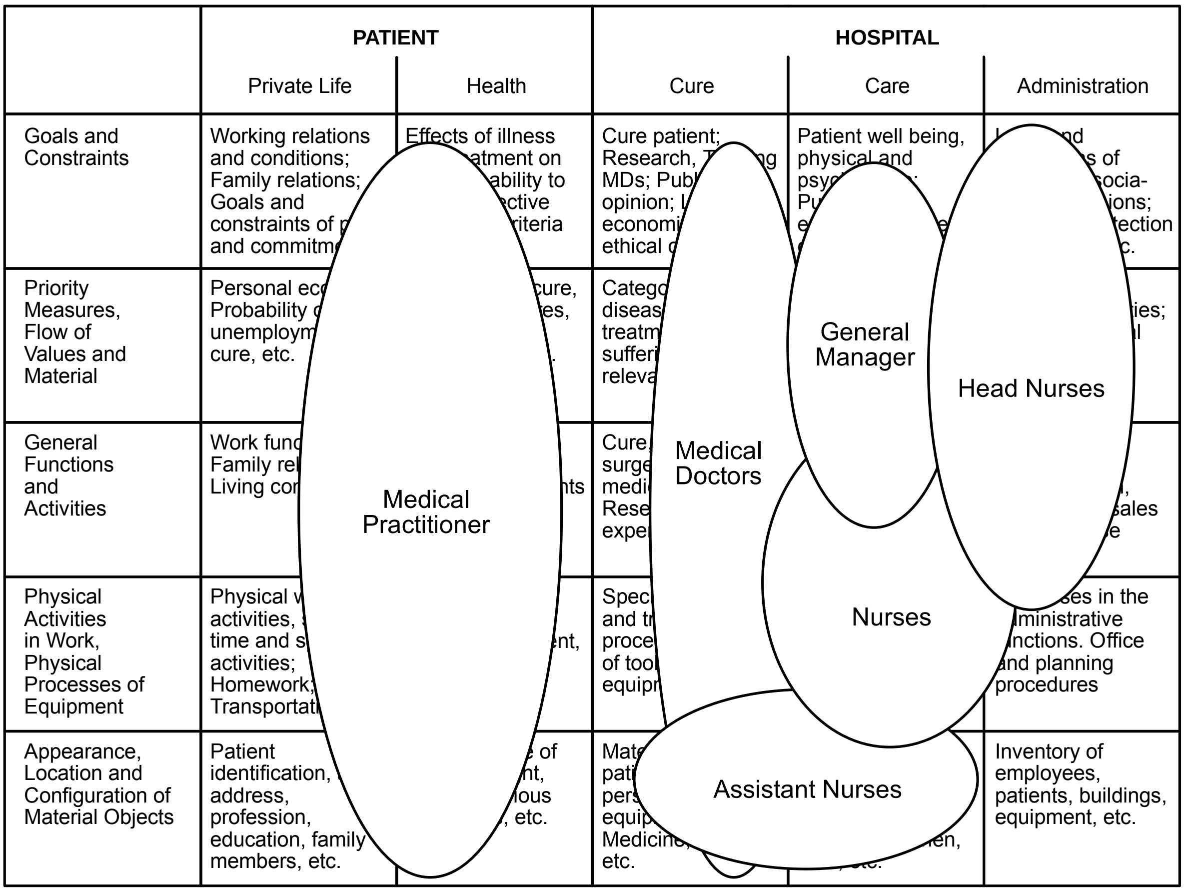

Figure 15 Stakeholders concerned with the treatment of patients in a hospital mapped onto the work domains in Table 1. Adapted from Rasmussen, Pejtersen & Schmidt (1990), with permission.

Such insights are possible because Rasmussen et al.'s (1990, 1994) representation of the health care system differentiates between work domains and object worlds or, in other words, between work domains and stakeholders' views of those work domains. Although Burns and Vicente (2000) observed similar interactions between stakeholders, object worlds, and work domains in their study, their representation of the engineering design system could not depict those interactions because their work domain models were not independent of stakeholders and their object worlds. Thus the representation of the health care system is a more powerful model because it can accommodate observations of how work is achieved in that system[3].

It is also important to point out that the representation of the health care system in Figure 15 is consistent with the theoretical underpinnings of work domain analysis. Whereas work domains are event-independent, stakeholders and their object worlds may vary as a function

[3] I should note that it is not my intention to single out Burns and Vicente (2000) for criticism. As I indicated earlier, except for Rasmussen et al. (1990, 1994), all other researchers who have modelled multiple stakeholders' perspectives have produced the same type of representation as Burns and Vicente have done.

of the situation, or over time, as indicated during the earlier discussions on team or organisational design. For example, the roles of head nurses and assistant nurses, and thus their object worlds, may shift or adapt in response to local contingencies, while the constraints associated with the work domains of cure, care, and administration in the health care system remain relatively constant. Hence maintaining the distinction between work domains, which are event-independent, and stakeholders and their object worlds, which are not, is important.

The challenge I grappled with, then, was how to formulate the guidelines for work domain analysis so that representations produced are consistent with that of the health care system, rather than the engineering design system, when modelling multiple stakeholders' perspectives. Without delving into the details of the guidelines, the answer lies in how the boundaries for a work domain analysis are formulated. That is, the boundaries must be formulated in a way that is independent of any specific actors, even when one wants to model the perspectives of particular stakeholders (Naikar, in press).

7.4 Further Methodological Developments

There are some other methodological developments in cognitive work analysis, which I cannot describe in detail here. For control task analysis, these include a new modelling tool called the contextual activity template (Naikar, Moylan & Pearce, 2006), a strategy for building decision ladder models (Elix & Naikar, 2008), and knowledge-elicitation techniques (Lamoureux & Chalmers, 2009). For worker competencies analysis, the main methodological development is a skills, rules, and knowledge inventory (Kilgore, St-Cyr & Jamieson, 2009).

8. Beyond Work Domain Analysis

The final stage of research in cognitive work analysis that this essay addresses is the recent emphasis on the dimensions of the framework subsequent to work domain analysis (Figure 3). These dimensions have not been neglected completely, as is evident from the preceding discussion. However, the majority of work, by far, has focused on work domain analysis.

The initial work on the other dimensions has focused on exemplifying their concepts and investigating their applications (e.g., Bisantz & Burns, 2009; Jenkins, Stanton, Salmon & Walker, 2009; Lintern, 2009; Naikar, 2006). The book edited by Bisantz and Burns also contains chapters that offer a preliminary exploration of the form the subsequent dimensions might take beyond how they are currently understood. In the following discussion, I highlight some of the challenges associated with the concepts and methodology of the subsequent dimensions using strategies analysis as an example. I believe that the work of the naturalistic decision making community is relevant for addressing these challenges, even more so since it has expanded its program to encompass functions other than decision making.

8.1 Strategies Analysis

Strategies analysis has several distinctive characteristics (Naikar, 2006, 2010, in press; Rasmussen et al., 1994; Vicente, 1999). First, this dimension of analysis is not concerned with specifying detailed sequences of actions or mental operations. Instead, it is concerned with defining categories of cognitive procedures, which are idealised, abstract descriptions of particular processes.

Second, strategies analysis recognises that several strategies are usually possible for performing a single activity. This dimension of analysis, therefore, involves examining the range of strategies that are possible for particular activities. Pejtersen (1979), for example, established that library staff and users could adopt many different strategies for finding material or information that satisfy their needs, namely, search by analogy, bibliographical strategy, analytical search, empirical search, and browsing strategy.

Similarly, Rasmussen and Jensen (1973) found that electronic technicians could adopt many different strategies for diagnosing faults in computer equipment. For instance, technicians could adopt a pattern recognition strategy (Figure 16). That is, a technician may recognise a pattern of data from the failed equipment as being familiar and associate that pattern with the cause of the fault or a task to perform, for example. Alternatively, technicians could adopt a hypothesis-and-test strategy (Figure 17). This is a more demanding cognitive strategy whereby, stated briefly, a hypothesis about the failed equipment is applied to a model of the normal equipment to produce a model of the hypothetical failed condition. The model of the hypothetical failed condition is then compared with observations of the failed equipment. If there is a match, the hypothesis is accepted. If not, it is rejected, and either another hypothesis is tested or an alternative strategy is adopted.

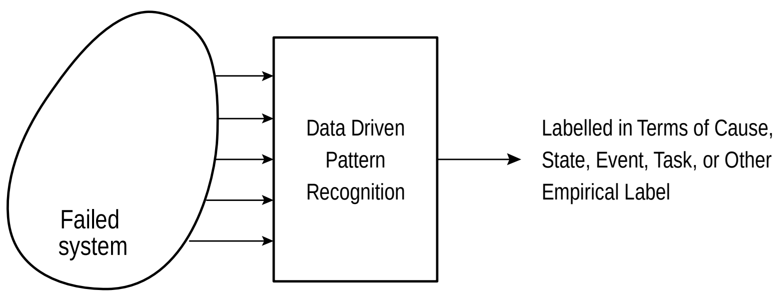

Figure 16 Pattern recognition strategy for electronic troubleshooting. Adapted from Rasmussen, J. (1981). Models of mental strategies in process plant diagnosis. In J. Rasmussen & E. B. Rouse (Eds.), Human detection and diagnosis of system failures *(pp. 241-258). © 1981 Plenum Press (Figure 4), with kind permission from Springer Science+Business Media B.V.*

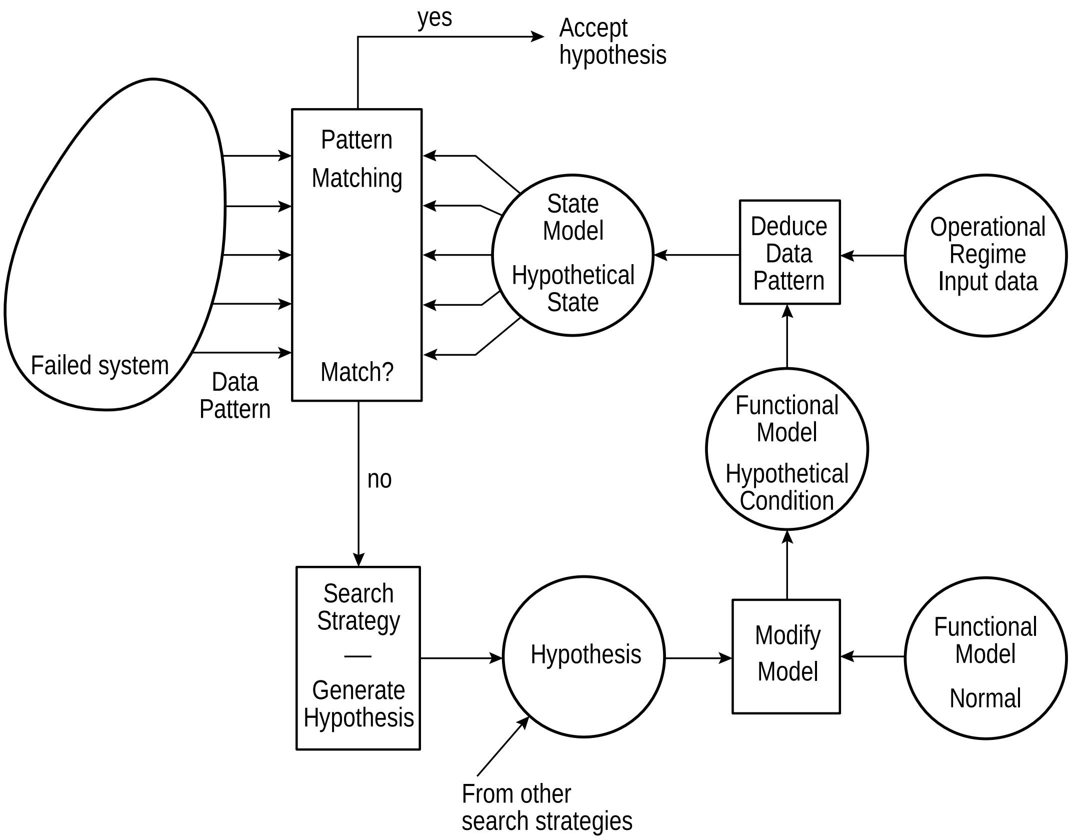

Figure 17 Hypothesis-and-test strategy for electronic troubleshooting. Adapted from Rasmussen, J. (1981). Models of mental strategies in process plant diagnosis. In J. Rasmussen & W. B. Rouse (Eds.), Human detection and diagnosis of system failures *(pp. 241-258). © 1981 Plenum Press (Figure 4), with kind permission from Springer Science+Business Media B.V.*

Third, strategies analysis recognises that actors often shift between multiple strategies while performing an activity. The strategies that actors adopt at any given moment vary as a function of their individual preferences, the demands of the situation, and the resource requirements of each strategy such as the amount of time, memory, or knowledge they require. Accordingly, by identifying the design requirements of multiple strategies, it becomes possible to create systems that provide workers with the flexibility to switch seamlessly between those strategies, depending on their individual preferences or judgment as to which strategy is best given the resource requirements and situational demands.

Fourth, strategies analysis is concerned with identifying the set of strategies that is possible, not just those workers use. Workers might ignore strategies that are resource intensive but, as a consequence, they might not make use of some very effective strategies. For instance, the hypothesis-and-test strategy described earlier was not favoured by electronic technicians because it is resource intensive, but this strategy has the advantage of being suitable for dealing with unfamiliar and complex faults. The resource requirements of a strategy can be manipulated through design, for example, by creating effective displays or offloading demanding aspects of a strategy to automation. Consequently, workers will be able to adopt strategies they otherwise might not use.

One of the key challenges of strategies analysis, then, is defining the set of strategies that is possible for any given system. The set of possible strategies goes beyond those that workers spontaneously adopt to include those workers could adopt, particularly if they were provided with appropriate support (Figure 18). Nevertheless, the strategies that workers spontaneously adopt, given the capabilities or constraints of the human cognitive system, are an essential subset. A key source of information for this subset of strategies is naturalistic decision making research. For example, Klein's (1989, 1998) recognition-primed decision making model describes a strategy that experts use for decision making in familiar situations and under demanding conditions such as high time pressure. This strategy has been found to be relevant to experts in a range of systems including firefighting, military, and medical systems. Thus, when performing strategies analysis for the same systems, a significant leverage point for analysis and design is provided by the fact that the recognition-primed decision making strategy has previously been studied and described in detail. Accordingly, with the in-depth study of functions other than decision making, such as sense making, planning, and problem detection, additional leverage points are possible for strategies analysis. This is one reason that the recent expansion in the focus of naturalistic decision making research to encompass functions other than decision making is of significant note.

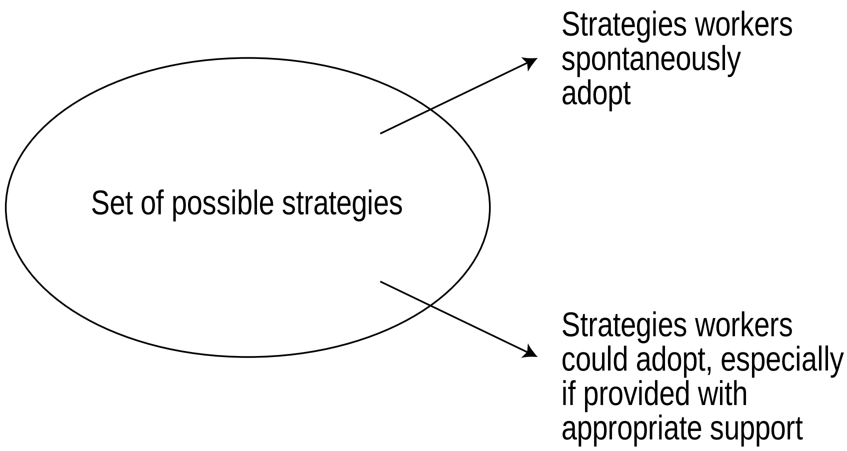

Figure 18 The set of possible strategies for any given system includes strategies that workers spontaneously adopt as well as strategies they could adopt, especially if they were provided with appropriate support.

9. Conclusion

In conclusion, although much has been achieved with cognitive work analysis over the last few decades, much remains to be done. Based on empirical studies of how work is achieved in naturalistic settings, Jens Rasmussen and his colleagues have provided us with a solid foundation for work analysis. This framework, which focuses on examining the possibilities for work within a set of boundaries or constraints, promotes designing for adaptation (Rasmussen et al., 1994; Rasmussen, 1986).

The EID framework (Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1990, 1992), which was formulated from the concepts of cognitive work analysis, has been subjected to a comprehensive program of controlled experimental investigations. This research has demonstrated that EID can lead to better performance than that supported by existing interfaces for a range of systems. The EID program has addressed in part the limitations of the original research by the Risø group relating to the lack of experimental testing of concepts and the generalisability of those concepts to a variety of systems. Future work on EID will include extensions to this framework to incorporate, among other things, the other dimensions of cognitive work analysis as well as other work analysis techniques.

Novel applications of cognitive work analysis to problems other than interface design have been achieved largely in industrial settings. Some of these applications involve extensions to cognitive work analysis to encompass, for example, the development of new team or organisational designs. These applications have had an impact in industrial settings and have made a unique contribution to design relative to that of standard techniques, but empirical evaluation is lacking. For this type of evaluation to be achieved, a shift to a research setting may be necessary.

The methodological program on cognitive work analysis complements the seminal monographs by Rasmussen et al. (1994) and Vicente (1999), which focus on providing a comprehensive conceptual perspective of this framework. While a substantive start has been made on methodology, much more work is necessary, especially in relation to the dimensions subsequent to work domain analysis.

The future program on the subsequent dimensions will echo the historical development of cognitive work analysis by building on the research of a range of communities. Just as the work of Rochlin et al. (1987), for instance, had significant impact on the concepts of cognitive work analysis, the insights of other researchers, including those in the naturalistic decision making community, may be influential. A significant challenge for researchers will be to build on any insights in a way that remains faithful to the theoretical underpinnings of cognitive work analysis, which appears to offer a potent approach to design.

These achievements in cognitive work analysis are likely to spark significant interest in this framework over the next decade. This is already becoming evident in the growing number of publications on cognitive work analysis over the last few years, many by researchers and practitioners who are new to the area. The immediate result will be a proliferation of applications of cognitive work analysis, including many novel applications. Eventually, then, one of the biggest challenges for cognitive work analysis will be to support an integrated approach to *system* design.

Designing for adaptation is a complex problem that will not be resolved in a piecemeal fashion. It will not be resolved by just an ecological interface, as Vicente (2002) recognised, and as I have experienced, it will not be resolved by just a team design. Instead, all elements of a system's design must be systematically integrated in a way that explicitly supports this objective, which raises theoretical, methodological, and practical challenges. I believe that cognitive work analysis has the potential to meet these challenges, but the task will not be simple.

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11. References

Bennett, K. B., Posey, S. M., & Shattuck, L. G. (2008). Ecological interface design for military command and control. *Journal of Cognitive Engineering and Decision Making*, *2*(4), 349-385.

Bisantz, A. M., & Burns, C. M. (Eds.). (2009). *Applications of cognitive work analysis*. Boca Raton, FL: CRC Press.

Bisantz, A. M., Roth, E., Brickman, B., Gosbee, L. L., Hettinger, L., & McKinney, J. (2003). Integrating cognitive analyses in a large-scale system design process. *International Journal of Human-Computer Studies*, *58*, 177-206.

Borst, C., Suijkerbuijk, H. C. H., Mulder, M., & van Paassen, M. M. (2006). Ecological interface design for terrain awareness. *International Journal of Aviation Psychology*, *16*(4), 375-400.

Burns, C. M. (2000). Putting it all together: Improving display integration in ecological displays. *Human Factors*, *42*(2), 226-241.

Burns, C. M., & Hajdukiewicz, J. R. (2004). *Ecological interface design*. Boca Raton, FL: CRC Press.

Burns, C. M., & Vicente, K. J. (2000). A participant-observer study of ergonomics in engineering design: How constraints drive design process. *Applied Ergonomics*, *31*, 73-82.

Burns, C. M., Kuo, J., & Ng, S. (2003). Ecological interface design: A new approach for visualizing network management. *Computer Networks, 43*, 369-388.

Christoffersen, K., Hunter, C. N., & Vicente, K. J. (1996). A longitudinal study of the effects of ecological interface design on skill acquisition. *Human Factors*, *38*(3), 523-541.

Czaja, S. J. (1997). Systems design and evaluation. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (2nd ed., pp. 17-40). New York: John Wiley & Sons.

Davis, L. E., & Wacker, G. L. (1982). Job design. In G. Salvendy (Ed.), *Handbook of industrial engineering* (pp. 2.5.1-2.5.31). New York: Wiley.

Davis, L. E., & Wacker, G. L. (1987). Job design. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 431-452). New York: Wiley.

de Groot, A. D. (1965). *Thought and choice in chess*. The Hague, Netherlands: Mouton Publishers.

Duez, P., & Vicente, K. J. (2005). Ecological interface design and computer network management: The effects of network size and fault frequency. *International Journal of Human-Computer Studies*, *63*, 565-586.

Duncker, K. (1945). On problem solving. Trans. L. S. Lees. *Psychological Monographs, 58* (5, Whole No. 270).

Elix, B., & Naikar, N. (2011). Unpublished work on team designs for inhabited and uninhabited aerial vehicles for maritime surveillance. Defence Science and Technology Organisation, Fishermans Bend, VIC, Australia.

Hackman, J. R., & Oldham, G. R. (1980). *Work redesign*. Reading, MA: Addison-Wesley.

Hajdukiewicz, J. R. (1998). *Development of a structured approach for patient monitoring in the operating room*. Unpublished master's thesis, University of Toronto, Ontario, Canada.

Hajdukiewicz, J. R., Vicente, K. J., Doyle, D. J., Milgram, P., & Burns, C. M. (2001). Modeling a medical environment: An ontology for integrated medical informatics design. *International Journal of Medical Informatics*, *62*, 79-99.

Ham, D. –H., & Yoon, W. C. (2001a). Design of information content and layout for process control based on goal-means domain analysis. *Cognition, Technology & Work*, *3*(4), 205-223.

Ham, D. -H., & Yoon, W. C. (2001b). The effects of presenting functionally abstracted information in fault diagnosis tasks. *Reliability Engineering and System Safety*, *73*, 103-119.

Ham, D. -H., Yoon, W. C., & Han, B. T. (2008). Experimental study on the effects of visualized functionally abstracted information on process control tasks. *Reliability Engineering and System Safety*, *93*, 254-270.

Jamieson, G. A. (2007). Ecological interface design for petrochemical process control: An empirical assessment. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, *37*(6), 906-920.

Jamieson, G. A., Miller, C. A., Ho, W. H., & Vicente, K. J. (2007). Integrating task- and work domain-based work analyses in ecological interface design: A process control case study. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, *37*(6), 887-905.

Janzen, M. E., & Vicente, K. J. (1998). Attention allocation within the abstraction hierarchy. *International Journal of Human-Computer Studies*, *48*, 521-545.

Jenkins, D. P., Stanton, N. A., Salmon, P. M., & Walker, G. H. (2009). *Cognitive work analysis: Coping with complexity*. Farhnam, UK: Ashgate.

Jensen, A., Rasmussen, J., & Timmerman, P. (1963). *Analysis of failure data for electronic equipment at Risø* (Report No. 38). Roskilde, Denmark: Danish Atomic Energy Commission, Research Establishment Risø.

Kilgore, R. M., St-Cyr, O., & Jamieson, G. A. (2009). From work domains to worker competencies: A five-phase CWA. In A. M. Bisantz & C. M. Burns (Eds.), *Applications of cognitive work analysis* (pp. 15-47). Boca Raton, FL: CRC Press.

Klein, G. A. (1989). Recognition-primed decisions. In W. B. Rouse (Ed.), *Advances in man-machine systems research*, 5, 47-92. Greenwich, CT: JAI Press Inc.

Klein, G. A. (1998). *Sources of power: How people make decisions*. Cambridge, MA: The MIT Press.

Lamoureux, T. M., & Chalmers, B. A. (2009). Control task analysis: Methodologies for eliciting and applying decision ladder models for command and control. In A. M. Bisantz & C. M. Burns (Eds.), *Applications of cognitive work analysis* (pp. 95-127). Boca Raton, FL: CRC Press.

Lau, N., Jamieson, G. A., Skraaning, G., Jr., & Burns, C. M. (2008). Ecological interface design in the nuclear domain: An empirical evaluation of ecological displays for the secondary subsystems of a boiling water reactor plant simulator. *IEEE Transactions on Nuclear Science*, *55*(6), 3597-3610.

Lehner, P. E. (1991). Towards a prescriptive theory of team design. *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics: Decision Aiding for Complex Systems* (pp. 2029-2034). New York: IEEE.

Leveson, N. G. (1995). *Safeware: System safety and computers*. Reading, MA: Addison-Wesley.

Leveson, N. G. (2000). Intent specifications: An approach to building human-centered specifications. *IEEE Transactions on Software Engineering*, *26*(1), 15-35.

Lintern, G. (2009). *The foundations and pragmatics of cognitive work analysis: A systematic approach to design of large-scale information systems* (Edition 1.0). Retrieved from www.cognitivesystemsdesign.net.

Medsker, G. J., & Campion, M. A. (1997). Job and team design. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (2nd ed., pp. 450-489). New York: John Wiley & Sons.

Miller, A. (2004). A work domain analysis framework for modelling intensive care unit patients. *Cognition, Technology & Work*, *6*(4), 207-222.

Miller, A., & Sanderson, P. (2000). Modeling "deranged" physiological systems for ICU information system design. *Proceedings of the joint 14th Triennial Congress of the International Ergonomics Association/44th Annual Meeting of the Human Factors and Ergonomics Society (HFES/IEA 2000), 4* (pp. 245-248). Santa Monica, CA: HFES.

Miller, C. A., & Vicente, K. J. (2001). Comparison of display requirements generated via hierarchical task and abstraction-decomposition space analysis techniques. *International Journal of Cognitive Ergonomics*, *5*(3), 335-355.

Naikar, N. (2006). An examination of the key concepts of the five phases of cognitive work analysis with examples from a familiar system. *Proceedings of the 50th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 447-451). Santa Monica, CA: HFES.

Naikar, N. (2009). Beyond the design of ecological interfaces: Applications of work domain analysis and control task analysis to the evaluation of design proposals, team design, and training. In A. M. Bisantz & C. M. Burns (Eds.), *Applications of cognitive work analysis* (pp. 69-94). Boca Raton, FL: CRC Press.

Naikar, N. (2010). *A comparison of the decision ladder template and the recognition-primed decision model* (DSTO-TR-2397). Fishermans Bend, VIC, Australia: Defence Science and Technology Organisation.

Naikar, N. (in press). *Work domain analysis: Concepts, guidelines, and cases*. Boca Raton, FL: Taylor and Francis Group, LLC.

Naikar, N., Hopcroft, R., & Moylan, A. (2005). *Work domain analysis: Theoretical concepts and methodology* (DSTO-TR-1665). Fishermans Bend, VIC, Australia: Defence Science and Technology Organisation.

Naikar, N., Moylan, A., & Pearce, B. (2006). Analysing activity in complex systems with cognitive work analysis: Concepts, guidelines, and case study for control task analysis. *Theoretical Issues in Ergonomics Science*, *7*(4), 371-394.

Naikar, N., Pearce, B., Drumm, D., & Sanderson, P. M. (2003). Designing teams for first-of-a-kind, complex systems using the initial phases of cognitive work analysis: Case study. *Human Factors*, *45*(2), 202-217.

Naikar, N., & Sanderson, P. M. (1999). Work domain analysis for training-system definition and acquisition. *International Journal of Aviation Psychology*, *9*(3), 271-290.

Naikar, N., & Sanderson, P. M. (2001). Evaluating design proposals for complex systems with work domain analysis. *Human Factors*, *43*(4), 529-542.

Naikar, N., & Saunders, A. (2003). Crossing the boundaries of safe operation: An approach for training technical skills in error management. *Cognition, Technology & Work*, *5*, 171-180.

Pawlak, W. S., & Vicente, K. J. (1996). Inducing effective operator control through ecological interface design. *International Journal of Human-Computer Studies*, *44*, 653-688.

Pejtersen, A. M. (1979). Investigation of search strategies in fiction based on an analysis of 134 user-librarian conversations. In T. Henriksen (Ed.), *IRFIS 3 Conference Proceedings* (pp. 107-132). Oslo, Norway: Statens Biblioteks-och Informations Hoegskole.

Perrow, C. (1984). *Normal accidents: Living with high-risk technologies*. New York: Basic Books.

Rasmussen, J. (1968a). *Characteristics of operator, automatic equipment and designer in plant automation* (Risø-M-808). Roskilde, Denmark: Risø.

Rasmussen, J. (1968b). *On the reliability of process plants and instrumentation systems* (Risø-M-706). Roskilde, Denmark: Danish Atomic Energy Commission, Research Establishment Risø.

Rasmussen, J. (1969). *Man-machine communication in the light of accident records* (Report No. S-1-69). Roskilde, Denmark: Danish Atomic Energy Commission, Research Establishment Risø.

Rasmussen, J. (1974). *The human data processor as a system component: Bits and pieces of a model* (Risø-M-1722). Roskilde, Denmark: Danish Atomic Energy Commission, Research Establishment Risø.

Rasmussen, J. (1979). *On the structure of knowledge – A morphology of mental models in a man-machine system context* (Risø-M-2192). Roskilde, Denmark: Risø National Laboratory.

Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics*, *13*(3), 257-266.

Rasmussen, J. (1985). The role of hierarchical knowledge representation in decisionmaking and system management. *IEEE Transactions on Systems, Man, and Cybernetics*, *15*(2), 234-243.

Rasmussen, J. (1986). *Information processing and human-machine interaction: An approach to cognitive engineering*. New York: North-Holland.

Rasmussen, J., & Jensen, A. (1973). *A study of mental procedures in electronic trouble shooting* (Risø-M-1582). Roskilde, Denmark: Danish Atomic Energy Commission, Research Establishment Risø.

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive systems engineering*. New York: John Wiley & Sons.

Rasmussen, J., Pejtersen, A. M., & Schmidt, K. (1990). *Taxonomy for cognitive work analysis* (Risø-M-2871). Roskilde, Denmark: Risø National Laboratory.

Rasmussen, J., & Timmerman, P. (1962). *Safety and reliability of reactor instrumentation with redundant instrument channels* (Risø Report No. 34). Roskilde, Denmark: Danish Atomic Energy Commission, Research Establishment Risø.

Rasmussen, J., & Vicente, K. J. (1989). Coping with human errors through system design: Implications for ecological interface design. *International Journal of Man-Machine Studies*, *31*(5), 517-534.

Reason, J. (1990). *Human error*. Cambridge, UK: Cambridge University Press.

Reising, D. V. C., & Sanderson, P. M. (1998). Designing displays under ecological interface design: Towards operationalizing semantic mapping. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting* (pp. 372-376). Santa Monica, CA: HFES.

Reising, D. V. C., & Sanderson, P. M. (2000a). Testing the impact of instrumentation location and reliability on ecological interface design: Control performance. *Proceedings of the joint 14th Triennial Congress of the International Ergonomics Association/44th Annual Meeting of the Human Factors and Ergonomics Society (HFES/IEA 2000), 1* (pp. 124-127). Santa Monica, CA: HFES.

Reising, D. V. C., & Sanderson, P. M. (2000b). Testing the impact of instrumentation location and reliability on ecological interface design: Fault diagnosis performance. *Proceedings of the joint 14th Triennial Congress of the International Ergonomics Association/44th Annual Meeting of the Human Factors and Ergonomics Society (HFES/IEA 2000), 3* (pp. 591-594). Santa Monica, CA: HFES.

Reising, D. V. C., & Sanderson, P. M. (2002a). Work domain analysis and sensors I: Principles and simple example. *International Journal of Human-Computer Studies*, *56*(6), 569-596.

Reising, D. V. C., & Sanderson, P. M. (2002b). Work domain analysis and sensors II: Pasteurizer II case study. *International Journal of Human-Computer Studies*, *56*(6), 597-637.

Reising, D. V. C, & Sanderson, P. M. (2004). Minimal instrumentation may compromise failure diagnosis with an ecological interface. *Human Factors*, *46*(1), 316-333.

Rochlin, G. I., La Porte, T. R., & Roberts, K. H. (1987). The self-designing high-reliability organization: Aircraft carrier flight operations at sea. *Naval War College Review*, *40*, 76-90.

Schraagen, J. M., Chipman, S. F., & Shalin, V. L. (Eds.). (2000). *Cognitive task analysis.* Mahwah, NJ: Lawrence Erlbaum Associates.

Sharp, T. D., & Helmicki, A. J. (1998). The application of the ecological interface design approach to neonatal intensive care medicine. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting* (pp. 350-354). Santa Monica, CA: HFES.

Shepherd, A. (2001). *Hierarchical task analysis*. London: Taylor & Francis.

St-Cyr, O. (2006). *Sensor noise and ecological interface design: Effects of noise magnitude on operators' performance and control strategies*. Unpublished doctoral dissertation, University of Toronto, Canada.

St-Cyr, O. & Vicente, K. J. (2004). Sensor noise and ecological interface design: Effects on operators' control performance. *Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting* (pp. 538-542). Santa Monica, CA: HFES.

St-Cyr, O. & Vicente, K. J. (2005). Sensor noise and ecological interface design: Effects of increasing noise magnitude on operators' performance. *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting* (pp. 417-421). Santa Monica, CA: HFES.

Sundstrom, E., De Meuse, K. P., & Futrell, D. (1990). Work teams: Applications and effectiveness. *American Psychologist*, *45*(2), 120-123.

Treadwell, A., Yeung, J., Brady, A., & Naikar, N. (2011). Unpublished work on organisational design for the Royal Australian Air Force. Defence Science and Technology Organisation, Fishermans Bend, VIC, Australia.

Vicente, K. J. (1999). *Cognitive work analysis: Toward safe, productive, and healthy computer-based work*. Mahwah, NJ: Lawrence Erlbaum Associates.

Vicente, K. J. (2001). Cognitive engineering research at Risø from 1962-1979. In E. Salas (Ed.), *Advances in human performance and cognitive engineering research* (pp. 1-57). Oxford, UK: Elsevier Science.

Vicente, K. J. (2002). Ecological interface design: Progress and challenges. *Human Factors*, *44*(1), 62-78.

Vicente, K. J., Christoffersen, K., & Pereklita, A. (1995). Supporting operator problem solving through ecological interface design. *IEEE Transactions on Systems, Man, and Cybernetics*, *25*(4), 529-545.

Vicente, K. J., & Rasmussen, J. (1990). The ecology of human-machine systems II: Mediating "direct perception" in complex work domains. *Ecological Psychology*, *2*(3), 207-249.

Vicente, K. J., & Rasmussen, J. (1992). Ecological interface design: Theoretical foundations. *IEEE Transactions on Systems, Man, and Cybernetics*, *22*(4), 589-606.

Watson, M. O., & Sanderson, P. M. (2007). Designing for attention with sound: Challenges and extensions to ecological interface design. *Human Factors, 49*(2), 331-346.

Whitefield, A., Wilson, F., & Dowell, J. (1991). A framework for human factors evaluation. *Behaviour & Information Technology*, *10*(1), 65-79.

Woods, D. D. (1984). Visual momentum: A concept to improve the cognitive coupling of person and computer. *International Journal of Man-Machine Studies*, *21*, 229-244.

Xu, W., Dainoff, M. J., & Mark, L. S. (1999). Facilitate complex search tasks in hypertext by externalizing functional properties of a work domain. *International Journal of Human-Computer Interaction*, *11*(3), 201-229.

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19. ABSTRACT
This essay, which reviews the foundations, extensions, and challenges of cognitive work analysis, is based on a keynote address delivered at the 10th International Naturalistic Decision Making Conference held in Orlando, Florida from 31 May to 3 June, 2011. It describes the origins of cognitive work analysis and the utility of this framework for designing ecological interfaces, as well as for tackling a variety of other design challenges, particularly, the design of teams or organisations. Also featured in this essay is the formulation of a methodological perspective of cognitive work analysis, which complements the conceptual accounts provided by Rasmussen (1986), Rasmussen, Pejtersen, and Goodstein (1994), and Vicente (1999). Finally, this essay highlights the latest shift in research emphasis from work domain analysis, the first dimension of cognitive work analysis, to the subsequent dimensions of this framework.