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Cognitive work analysis: An influential legacy extending beyond human factors and engineering

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A R T I C L E I N F O

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A B S T R A C T

Jens Rasmussen's multifaceted legacy includes cognitive work analysis (CWA), a framework for the analysis, design, and evaluation of complex sociotechnical systems. After considering the framework's origins, this paper reviews its progress, predictably covering experimental research on ecological interface design, case studies of the application of CWA to human factors and engineering problems in industry, and methods and modelling tools for CWA. Emphasis is placed, however, on studying the nexus between some of the recent results obtained with CWA and the original field studies of human problem-solving that motivated the framework's development. Of particular interest is a case study of the use of CWA for military doctrine development, a problem commonly regarded as lying outside the fields of human factors and engineering. It is concluded that the value of CWA, even for such diverse problems, is likely to result from its conceptual grounding in empirical observations of patterns of human reasoning in complex systems.

1. Introduction

In the design of complex sociotechnical systems, cognitive work analysis (CWA) provides a distinctive perspective. Described as formative, this framework considers the constraints on actors' behaviour to be the primary unit of analysis for design, rather than the details of those behaviours (Rasmussen, 1986; Rasmussen et al., 1994; Vicente, 1999). While these constraints limit the possibilities for action available to actors, within these constraints actors still have many remaining degrees of freedom for behaviour. Therefore, designs based on constraints can promote worker adaptation to local contingencies, which cannot always be predicted a priori, within the boundaries on effective performance.

Table 1 summarises the essential features of CWA. This framework has five distinct dimensions, which focus on different kinds of constraints. In addition, each dimension has special modelling tools for constructing representations of constraints. Many of these modelling tools were part of the original descriptions of CWA (Rasmussen, 1986; Rasmussen et al., 1994), arising out of the work of Jens Rasmussen and his colleagues at the Risø National Laboratory in Denmark. However, the contextual activity template for activity analysis (Naikar et al., 2006) and the diagram of work organisation possibilities for social organisation and cooperation analysis (Naikar and Elix, 2015, 2016a, 2016b) are more recent additions that are consistent with the conceptual foundations of CWA.

The work of Jens Rasmussen, which is embodied in part by the concepts of CWA, has been lauded as representing "nothing less than a paradigm shift" (Moray, 1988, p.12). Moray's discourse focuses on the skills, rules, and knowledge taxonomy, as he sees this tool as having had the most widespread impact in discussions of complex human-machine systems. This observation may still be relevant, as the skills, rules, and knowledge taxonomy continues to motivate discussions in such diverse contexts as mental workload, human error, accident analysis, display design, and operator training, often independently of CWA. However, it is also true that other aspects of CWA have significantly greater prominence now than they had twenty or thirty years ago.

Arguably, the primary shift in thinking that CWA represents in the study of human-machine systems is the change in focus of design from actors' behaviours to system constraints, as intimated earlier. The prevailing thinking when CWA was conceived was that the design objective should be to support workers in executing specific behaviours. CWA fosters a different mindset. This mindset arises from the recognition that complex sociotechnical systems, being open systems, are exposed to unforeseen events and that

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Table 1
CWA dimensions, constraints, and modelling tools.

Dimensions	Constraints	Modelling tools
Work domain analysis	Work domain—constraints placed on actors by the physical, social, and cultural environment, including the system's purposes, values and priorities, functions, and physical resources	Abstraction-decomposition space, abstraction hierarchy
Activity analysis	Activity—constraints placed on actors by the activities necessary in the system to achieve the system's purposes, values and priorities, and functions with the available resources	Contextual activity template, decision ladder
Strategies analysis	Strategies—constraints placed on actors by the cognitive strategies that can be utilised for achieving the activities necessary in the system	Information flow map
Social organisation and cooperation analysis	Work organisation—constraints placed on actors by the ways in which work can be allocated, distributed, and coordinated in the system	Diagram of work organisation possibilities
Worker competencies analysis	Workers—constraints placed on actors by the ways in which the work demands of the system can be met given human cognitive capabilities and limitations	Skills, rules, and knowledge taxonomy

these events pose significant threats to system effectiveness. Consequently, the objective of promoting successful worker adaptation—irrespective of the circumstances—is critical. Given this intent, designs cannot be based on descriptions of the cognitive tasks or actions carried out by workers, as these cannot be fully anticipated a priori. Instead, to support adaptive problem-solving, designs must be specified in terms of the constraints that shape the behaviours that are possible in any situation.

The rest of this paper traces the evolution of CWA, from its origins to its subsequent development and impact. While its progress has been documented before (Naikar, 2012), this account places emphasis on the outcomes of the last four or five years. Moreover, this account examines the relationship of some recent advances in CWA to the conceptual origins of the approach in studies of human problem-solving in complex systems. Of particular note is a new application of CWA to military doctrine development (Brady et al., 2013; Naikar et al., 2014). Juxtaposed against the foundations of CWA and preceding applications of this framework within the fields of human factors and engineering, it becomes possible to examine the relevance of earlier insights on human reasoning, as revealed in the context of interface design particularly, to this novel problem area.

2. Foundations

CWA was conceived in the 1960s and 1970s by Jens Rasmussen and his colleagues at the Risø National Laboratory (Vicente, 1999, 2001). The aim of this organisation was to conduct research in support of the implementation of nuclear power in Denmark. CWA evolved specifically from a program in the Electronics Department, which was headed by Jens Rasmussen. The challenge this group faced, which led ultimately to the development of CWA, was how to advance the safety of nuclear power plant operations at a time when hardware systems were already performing with extremely high reliability.

In the early 1960s, the focus of Rasmussen's group had in fact been on hardware reliability. That is, the group was concerned with examining the reliability of nuclear reactor equipment and instrumentation (Jensen et al., 1963; Rasmussen and Timmerman, 1962). Their research investigated such issues as the probability of equipment failure and the degree of redundancy needed in backup systems to achieve high levels of safety. 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. What followed was a program that is inspiring for its vision, depth, and meticulousness.

First, Rasmussen sought to understand precisely why accidents eventuated despite increasingly high levels of hardware reliability. An analysis of major industrial accidents was conducted, which included 29 cases in the nuclear domain and 100 cases in the air transportation domain (Rasmussen, 1968a, 1968b, 1969). This study revealed that human error accounted for approximately three quarters of accidents, and that these errors arose when workers were confronted with unfamiliar events. As these events could not have been foreseen by analysts or designers, workers could not have been provided with pre-planned procedures for handling these occurrences. However, the analysis also showed that, in nearly all cases, workers could have formulated an appropriate response if the actual state of the system at the time had been known to them. These findings signified the importance of providing workers with the information they needed about the system to adapt their behaviour to the demands of a wide range of situations, including unforeseen events, and thus *finish the design* (Rasmussen and Goodstein, 1987).

In the 1970s, therefore, the focus of the Risø group shifted to human-machine reliability. A number of empirical studies were conducted with the intent of establishing a sound basis for designing safer human-machine systems. Many of these studies involved examining the problem-solving strategies of experienced workers as they carried out a variety of tasks that were representative of their normal jobs. One such study was concerned with electronic troubleshooting.

In this field study, Rasmussen and Jensen (1973) investigated the way in which professional technicians troubleshoot complex faults in commercially available electronic equipment. Their study involved the participation of six professional technicians, and it included eight different types of instruments, each with a particular fault. The investigation utilised verbal protocol methodology, so the 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 technicians' verbal protocols. All of the verbal protocols were then reviewed to determine if the information in them was captured effectively by the coding scheme. Changes were made to the coding scheme to eliminate any discrepancies with the verbal protocols, and the whole process was repeated until the coding scheme stabilised. The verbal protocols were then re-analysed with the final coding scheme. Fig. 1 shows some of the results of this process. Although the details are unclear, the illustrations provide a sense of the complexity of the analyses and the painstaking nature of Rasmussen and Jensen's (1973) work.

The results of this field study of electronic troubleshooting, and other such studies, revealed a number of patterns in how workers reason about complex systems during problem solving in a range of situations (Rasmussen, 1979, 1985), which are now well known.