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Chapter X: Understanding Cognitive Work

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X.1 Introduction

The purpose of this chapter is to provide some insight into how cognitive work is conceptualized and investigated in the tradition of cognitive systems engineering (CSE) advocated by David Woods and his colleagues, including in particular Erik Hollnagel and Emilie Roth. First I survey recent treatments of cognitive work analysis (CWA) and cognitive task analysis (CTA). Then I introduce the idea of joint cognitive systems and the cognitive systems triad—these are concepts that have been fundamental in Woods' work for decades. Following that I describe a model for human performance analysis that for some time has guided investigations into how people cope with complexity and has lain at the heart of the way Woods and his colleagues approach analysis and design of cognitive work. I then describe an investigative context dubbed "staged worlds" that Woods and colleagues use to preserve authenticity while enhancing the efficiency of investigations and I illustrate the use of staged worlds with a recently published emergency medical response example (Smith, Bentley, Fernandez, Gibson, Schweikhart, & Woods, 2013). Finally, the model of human performance analysis and the above methods lead to “laws” that describe joint cognitive systems at work.

X.2 Analysing Cognitive Work Through CWA and CTA

Many approaches have emerged in CSE and cognate fields of inquiry for investigating cognitive work. Two widely-used approaches are cognitive task analysis (CTA) and cognitive work analysis (CWA). Given the many excellent recent reviews of CTA and CWA there is little need for a further detailed review of their principles and methods. However it is worth pointing to the origins of the approaches and to the recent treatments of them.

The principles that underlie both approaches to understanding cognitive work reach back over 30 years, to the genesis of cognitive systems engineering (Hollnagel & Woods, 1983) and to European studies of human-machine systems conducted in the decade before the Three-Mile Island accident in 1979 (see treatments in Sheridan & Johannsen, 1976; Rasmussen & Rouse, 1981 as well as overviews in Flach, 2016; Le Coze, 2015, 2016, and others). Since the early 1980s, Woods has been a core contributor and leader in the development and expression of those principles, and in the development and expression of methods for understanding cognitive work.

Within CSE, CTA and CWA are often compared and contrasted, given that they are core methods for analyzing cognitive work. CSE has been defined as the analysis, modeling, design and evaluation of complex sociotechnical systems so that workers can do their work and carry out tasks more safely, and with greater efficiency. In the context of CSE, the term "cognitive work" is usually used to represent the individual and collective sense-making activities of workers and other agents in complex sociotechnical systems. The phrase "analysis of cognitive work" usually covers activities that CSE researchers carry out when performing CWA or CTA. The main focus of this chapter is Woods' contributions not only to the analysis of cognitive work but also to the design of cognitive work. As will be seen, Woods and colleagues refer to their analytic activities as CTA, and their design activities are guided by laws that govern cognitive work, including laws that govern joint cognitive systems at work.

The term CWA is by convention reserved for the systematic approach to analyzing the constraints operating on cognitive work that emerged from the work of Rasmussen and his colleagues at Riso National Laboratories in Denmark (Rasmussen 1986; Rasmussen, Pejtersen, & Goodsein, 1994; Vicente, 1999; LeCoze 2015; 2016). CWA focuses on analyzing the constraints that shape cognitive work, using a family of analytic templates that guide the identification of those constraints and their interactions. The term CTA is best reserved for approaches to analyzing cognitive work other than CWA, but those approaches may nonetheless share some of the theoretical commitments of CWA because they emerge from the same history. A similar distinction between CWA and CTA is respected in Lee and Kirlik's (2013) handbook of cognitive engineering, with its separate chapters on CWA (Roth & Bisantz, 2013) and CTA (Crandall & Hoffman, 2013). Again, however, the fact that a distinction can be made should not obscure similarities between the two approaches to the analysis of cognitive work and the intertwined history of their development.

As noted, CTA and CWA have been the subject of many recent authoritative reviews, making a repetition of their fundamentals unnecessary. CWA has received several thorough treatments over the 30 years or so of its existence. The foundational work of Rasmussen is available through the Rasmussen (1986) and Rasmussen, Pejtersen, and Goodstein (1994) monographs. The work received a subsequent pedagogical interpretation in Vicente (1999) and many aspects of Rasmussen's way of analyzing cognitive work have been the subject of a recent special issue of *Applied Ergonomics*. Further monographs and edited books on CWA include Bisantz and Burns (2009), Jenkins, Stanton, Salmon, and Walker (2009), Lintern (2013) and Naikar (2013). Review chapters focusing on CWA include Sanderson (2003) and Roth and Bisantz (2013). Many recent treatments of CWA offer novel templates intended to help analysts apply the principles of CWA more effectively at each phase, or to link analyses more effectively with analyses at other phases (Naikar, 2013; Cornelissen et al., 2012; Hassall & Sanderson, 2013; Ashoori & Burns, 2010).

Since 2000, CTA has also been thoroughly reviewed in monographs or edited books such as those by by Schraagen, Chipman and Shalin (2000), Crandall, Klein, and Hoffmann (2006), and in Hoffman and Militello's excellent monograph on CTA methods (2008). Recent reviews of CTA also include Crandall and Hoffman (2013). Treatments of CTA often describe different methods of eliciting information about cognitive work. The most helpful treatments also describe the process of understanding the phenomenology of work in a lawful way. For example, as we will see, Woods has proposed laws that express important generalities about how people and technology interact (Woods & Hollnagel, 2006). Those laws have been inferred from investigating and analyzing the successes and failures of human-system integration in many domains—in other words, from different CTAs conducted in widely differing industries.

Reviews that cover both CTA and CWA include Bisantz and Roth (2008) and Hoffman and Militello (2009). CTA and CWA were also covered in a major review of methodological challenges for a science of sociotechnical systems and safety (Waterson, Robertson, Cooke, Militello, Roth, & Stanton, 2015).

X.3 Joint Cognitive Systems and the Cognitive Systems Triad

From the CSE perspective, the entity performing cognitive work—and therefore the entity to be investigated—is not just the individual human actor. Since their formulation of CSE, Woods and colleagues have brought a "joint cognitive systems" perspective to the development of useful theoretical frameworks for understanding cognitive work (Hollnagel & Woods, 1983; Woods, 1985). Hollnagel and Woods (2005) define a *cognitive system* as "a simple system capable of anti-entropic behavior" (p. 78) which could be a human or an intelligent device of some kind. They then define a *joint cognitive system* as a combination of a cognitive system plus (a) one or more further cognitive systems and/or (b) one or more objects (physical artefacts) or rules (social artefacts) that is used in the joint cognitive system's work. Clearly, there are many forms that a joint cognitive system can take that extend far beyond the individual.

A key feature of Woods' approach to the analysis of cognitive work has been the so-called *cognitive systems triad* (Woods, 1988; Woods & Roth, 1988) which reflects the fact that a joint cognitive system carries out its functions in a context or environment.

The cognitive systems triad shows the interplay of *agents* (people, cognitive systems, joint cognitive systems), *artifacts* (technology, representations), and the external *world* (demands, constraints, dynamics). An early version of the cognitive systems triad (Woods, 1988) is shown at left of Figure 1, and a later version, annotated with relevant elements (Woods, Tinapple, Roesler, & Feil, 2002) is shown at right of Figure 1.

Insert Figure 1 about here

As Woods notes, the cognitive systems triad is not analytically decomposable because when cognitive work takes place in complex sociotechnical systems, its three elements are inextricably linked to each other. In other words, one cannot understand cognitive work by examining each of the three elements independently of the other—by studying agents alone, artifacts alone, or the external world alone—and then trying to combine them. This fact imposes constraints on how CTA should be performed: the connections between agents, artifacts and the external world cannot be ruptured. Accordingly, data supporting a CTA must come from qualified agents addressing authentic demands from their domain of work, using representative work artifacts and tools, as we will see in the Smith et al. (2013) example presented later in this chapter.

X.4 Theory-Driven Analysis and Design

Many treatments of CTA and CWA emphasise the process rather than the purpose of performing analyses of cognitive work. A model that has appeared in different forms for over 35 years, and that reappears in the writings of Woods and colleagues, provides one way of thinking about the purpose of CTA. The model is most succinctly described diagrammatically, and an example is shown in Figure 2. The diagram distinguishes data-driven and concept-driven forms of analysis, and helps us focus on *why* analyses of cognitive work are done, as much as on how analyses are done.

The history of the diagram points to the intentions behind it. Early research at Riso National Laboratories about how best to support the cognitive work of nuclear power plant (NPP) operators produced powerful ways of analyzing records of cognitive work, some of which are summarized in a Riso technical report by Hollnagel, Pedersen and Rasmussen (1981). The approach is also described briefly for the US audience in one of Woods' and Hollnagel's earliest joint papers (Woods & Hollnagel, 1982).

During their analysis of incidents, events, and accidents in nuclear power plants, Hollnagel et al. were confronted with many different sources of human performance data: event reports, post-incident reviews and interviews, recordings of performance in training simulators specific to a particular plant, and recordings of performance in more generalized research simulators. The challenge was to find a "common analytical framework" that would help researchers arrive at a conceptually coherent account of operator cognitive work, capable of both providing insight into the particular events examined and providing theoretical constructs that could be generalized and tested in other contexts. The analyses were being performed in the aftermath of the Three-Mile Island accident in 1979, and the framework was intended to be a practical tool for engineers rather than a formal model for academics (Erik Hollnagel, personal communication, 24 January 2016).

Hollnagel et al. (1981) describe their process of converting raw data into forms that are useful for various purposes—initially, for deciding on training programs for NPP operators. The inputs and outputs of the process are shown in Figure 2, which is a reworking for present purposes of earlier versions of the diagram that appear in Hollnagel et al. (1981), Hollnagel (1986), Xiao and Vicente (2000), Woods and Hollnagel (2006), Hollnagel (2015) and other locations. The reworking in Figure 2 rearranges the analysis and prediction columns for better flow, rewords some elements for better understanding and, incidentally, corrects a small error that crept into prior reproductions, for example in Woods and Hollnagel (2006).

X.4.1 Left side of human performance analysis diagram

The boxes in the CTA (left) column of the diagram show that analysts build formal, context-free accounts of cognitive work through a series of steps that combine data and impose theoretical interpretations until, at the top, a context-free theoretical description is reached that can in principle be applied to other contexts. We can view this as a process of abstraction from a context-specific account to a context-independent account (Xiao & Vicente, 2000).

Insert Figure 2 about here

First, at the start of the process, which is seen at the bottom of the diagram, event reports, reviews, interviews, observations, and simulator-based human performance data are the *raw event data*. Second, once the raw event data are aggregated and rearranged into a whole, for example by being placed on a timeline, and different forms of data are integrated (for example, performance logs and verbalization are aligned) they become *integrated event data* providing a coherent account of an individual's work processes, in professional or domain terms, but without interpretation. Third, the records of actual performance are then redescribed in a more formal language to become *analysed event data*, where the elements of actual performance are classified into categories that may emerge from pre-existing theories, ontologies or templates relating to cognitive work, such as general information-gathering strategies or as problem solving steps the operator uses to handle specific problems in the domain. The analysed event data start to offer an interpretation of why the data are as they are.

Fourth, from here, data from multiple individual cases of performance are aggregated to arrive at *conceptual descriptions* for the specific context under examination. Recurring categories are noted, and the patterns of similarities and differences across the multiple cases are noted, still using the formal language introduced for analysed event data, along with factors that might account for the similarities and differences. Fifth, what Hollnagel et al. (1981) called a *competence description* removes reference to the specific context or contexts in which the raw data were collected. It provides a description of the "behavioural repertoire" of the operator for the general class of situations examined, and not for any particular situation or even for any particular domain. The conceptual description is placed within a broader theoretical framework that can be generalized to other contexts.

X.4.2 Right side of human performance analysis diagram

The boxes in the CTD (right) side of Figure 2 handle performance prediction; they show how an evaluation can be performed of factors likely to change cognitive work, such as new work tools or new work processes. As Hollnagel et al. (1981) stated, "the competence description is … essentially the basis for performance prediction during system design" (p. 12). We can consider the process of moving from the competence description to raw data as a process of instantiation (Xiao & Vicente, 2000). However, the theme of instantiation is not pursued further in the 1981 paper. The theme of instantiation reappears in Hollnagel's (1985) discussion of cognitive performance analysis, where a more explicit discussion of a top down process of instantiation is offered. The Hollnagel (1985) diagram also specifies a top-down process of prediction, as do the more fully worked diagrams in Woods and Hollnagel (2006) and Woods (2003) – and the version in Figure 2.

In the CTD (right) or prediction side of Figure 2, the analyst starts with theories of competence, and can conjecture what the required *competence* will be for the desired cognitive work within the system. The means of support for that competence then needs to be engineered or implemented, and tested. Design specifications can be identified that produce an account of the desired *prototypical performance*, the presence of which can be tested by trying out the design with one or more workers in authentic professional contexts to produce instantiations of the prototypical performance, or *formal performance*. Formal performance is inferred from *performance fragments* combined into accounts of *actual performance* and interpreted in the appropriate theoretical frame.

The CTD or prediction side of Figure 2 is where abstract concepts can be put "into empirical jeopardy as explanatory or anticipatory tools in specific situations" (Woods & Hollnagel, 2006). A fuller description is given in Woods and Hollnagel (2006) that includes the potential for interplay between processes on the two sides of the diagram.

> *The processes [in the diagram] capture the heart of Neisser's perceptual cycle as a model of robust conceptualization and revision ... moving up abstracts particulars into patterns; moving down puts abstract concepts into empirical jeopardy as explanatory or anticipatory tools in specific situations. This view of re-conceptualization points out that what is critical is not one or the other of these processes; rather, the value comes from engaging in both in parallel. When focused on abstract patterns, shift and consider how the abstract plays out in varying particular situations; when focused on the particular, shift and consider how the particular instantiates more abstract patterns ... This is a basic heuristic for functional synthesis, and the interplay of moving up and down helps balance the trade-off between the risk of being trapped in the details of specific situations, people, and events, and the risk of being trapped in dependence on a set of concepts which can prove incomplete or wrong. (p. 49)*

The above description makes it clear that the cognitive work of the analyst who is investigating cognitive work requires tools that support rapid shifts between raw data and interpretation, and between different perspectives. Software tools for exploratory sequential data analysis (Sanderson & Fisher, 1994) such as MacSHAPA (Sanderson et al., 1994) were an attempt to provide such support. It is not clear that the current generation of software tools presents any great improvement in supporting the analyst's shifts between raw data and theoretical interpretations and between perspectives—robust tools for supporting the work of analysts analyzing cognitive work have still to be created.

X.4.3 Uses of the human performance analysis diagram

The model of human performance analysis outlined in Hollnagel et al. (1981) was quickly absorbed into Woods' thinking. For Hollnagel, Woods, and their students and close colleagues, it has guided methods for performing field investigations ever since. For example, Roth, Christian, Gustafson, Sheridan, Dwyer, Gandhi, Zinner and Dierks (2004) and Roth and Patterson (2005) show that field investigations guided by the model can benefit from existing conceptual frameworks but also provide a means to develop new conceptual frameworks and new insights. Saleem, Patterson, Militello, Render, Orshansky & Asch (2005) used the model to analyse VA providers' interactions with computerized clinical reminders. As will be seen in the next sections, Woods (2003) extended the lessons of the model to 'staged world' studies, showing how process tracing of performance in such studies can lead to high-level functional accounts of competence. Most recently, the model was revisited by Hollnagel (2015) in a resilience engineering chapter on finding patterns in everyday healthcare work.

Two widely-cited examples of uses of the Hollnagel et al. (1981) framework are provided by Xiao and Vicente (2000) who used variants of the framework to describe (1) the process of discovering the nature of anesthesiologists' peri-operative preparations in Xiao (1994), which reflects a process of abstraction and (2) the evaluation of ecological interface design principles for visual display design, which reflects a process of instantiation (Vicente, 1991).

In the first case, involving the process of abstraction, Xiao (1994) investigated how anesthesiologists prepare their management of a patient, given that each patient is different and given that patient monitoring technology provides only partial views of the true state of the patient. Xiao aggregated field notes and recordings to arrive at an integrated description of individual anesthesiologists' planning performance. Specific preparatory strategies were then noted in the language of the domain itself, such as prefilling and systematizing the layout of syringes. Further abstraction was achieved by describing the purpose of the anesthesiologists' strategies in more general terms, such as providing reminders, offloading workload, etc. Finally, a competence description was achieved through broad generalisations transcending specific situations, individuals, and contexts, such as statements about how expert practitioners in complex worlds manage complexity: "Experienced practitioners reduce response complexity through anticipating future situations, mental preparation, and reorganizing the physical workspace" (Xiao & Vicente, 2000; p. 98). Knowledge of expert competencies could, in turn, guide the search for further instances or for counterinstances in a dataset, or could guide tests of generalizability to other domains.

In the second case, involving instantiation, Vicente (1991) used a theory of competent management of system disturbances to create a visual display design that would produce performance data that would confirm or refute the theory, in a process of instantiation. Again, "designs are hypotheses about how artifacts shape cognition and collaboration" (Woods, 1988; p. 168). Starting at the top level, and based on principles of ecological interface design (Vicente & Rasmussen, 1990; 1992) Vicente's theoretical claims were that (1) operators are better able to handle unanticipated variability if they can engage in knowledge-based behavior, and (2) knowledge-based behavior is best served by a display that provides a representation of the work domain that is based on an abstraction hierarchy. At the second level, two interfaces instantiated the theory in a concrete context – control of a thermodynamic process – with one interface embodying ecological interface design (EID) principles and the other not. At the third level the objective was to construct a task that would provide "formal performance data" – aggregated experimental data capable of clearly reflecting changes in performance related to the presence or absence of EID principles. At the fourth and fifth levels the concern was with identifying and collating the most appropriate information from participants to build the formal account.

So, on the one hand, Figure 2 describes a CTA process that helps us abstract lawful relationships about the interaction of people and technology. On the other hand, Figure 2 describes a CTD process of applying and testing those laws through changing one aspect of the cognitive systems triad, and for much of Woods' work that has involved changing the artifacts—the technology. Woods' work on CTA has been tightly linked to the extraction of regularities about sociotechnical systems that can be applied to different domains, and the generation of designs likely to support successful joint cognitive work. Too often, CTA is described in isolation from CTD, but Figure 2 makes it clear why CTA must be considered hand in hand with CTD. Further information about CTD from this perspective is available in Hollnagel (2003) and Woods (2003).

X.5 Shaping the Conditions of Observation with Staged Worlds

There are many ways in which analysts can investigate authentic professional work, each of which has advantages and disadvantages. In very early work, Woods (1985) identified an "observation problem" in psychology and particularly in the study of complex cognitive work within joint cognitive systems. Woods (1985) distinguished three mutual constraints on the ability to observe cognitive work – (1) *specificity*, which is the degree of control exercised by the observer and the repeatability of the analysis, (2) *apparent realism or face validity*, which is the fidelity of the observed work context with respect to the actual work context of interest, and (3) *meaningfulness*, which is the theoretical richness of the resulting account and its ability to be applied in other contexts.

One of the most important concerns in understanding cognitive work remains how to maximize the leverage gained from interactions with professionals in authentic work contexts, particularly with respect to the above meaningfulness dimension. Over the last 35 or more years, CSE methods have included naturalistic observation, think aloud protocols, structured interview techniques such as the critical decision methodology, and behavioural or performance logs of professionals in their work contexts. Amongst these methods is Woods' idea of shaping the conditions of observation through *staged worlds* as a method for studying cognitive work.

X.5.1 Staged worlds

Staged worlds are not often discussed in reviews of CWA and CTA although they were noted in the reviews by Bisantz and Roth (2008) and Hoffman and Militello (2008). Despite this, staged worlds are an important tool in Woods' approach to understanding cognitive work.

In order to illustrate whether the conditions of observation preserve the interlinked relationships in the cognitive triad, Woods (1993; 2003; and elsewhere) contrasts staged worlds with *natural history methods* and *spartan laboratory experiments*. Natural history methods are effectively field studies, where the operation of the cognitive systems triad is undisturbed. Spartan laboratory experiments, in contrast, usually remove most of the properties of the external world and sometimes also of the agents and artifacts, in the interest of "control".

Staged worlds are effectively simulations of work contexts that focus on specific situations or problems that practitioners may encounter and that preserve key interrelationships in the cognitive systems triad. The effectiveness of a staged world rests in how effectively the essential properties of the cognitive systems triad are preserved in the experiences created—experiences that emerge from the relationship between people, technology, and work. A staged world can create situations that might arise only very seldom in naturalistic observation, while still preserving key properties of the work domain that create an authentic, immersive experience for practitioners. As a result, a staged world is an effective and efficient means of investigating cognitive work. A staged world can be used to probe strategies, trace cognitive processes, explore the impact of new work systems, and so on. It is therefore a powerful tool for analyzing cognitive work and for understanding how practitioners cope with complexity.

The above description of natural history methods, staged worlds, and Spartan laboratory experiments might suggest that only three distinct categories of observation exist, which is patently not the case. Instead, the three methods exist on a continuum. For example, a natural history method may introduce contrasts by sampling situations or contexts, or field experiments may be possible by inserting probes or prototypes into the full operational work environment. As a further example, a staged world may reproduce the work environment and its demands with different levels of breadth and depth. Some of the possibilities are discussed in Sanderson and Grundgeiger (2015) in the context of how workplace interruptions in healthcare have been studied, using Woods' (1985) tension among specificity, realism, and meaningfulness.

X.5.2 A staged worlds example in emergency medicine

A recent paper in *Annals of Emergency Medicine* co-authored by Woods (Smith et al., 2013) illustrates the use of staged worlds to support a CTA. In the paper the principles and methods of CTA are exposed for the benefit of an audience of emergency medical and paramedical professionals. It is therefore worth describing this example in greater detail.

Smith et al. (2013) presented a cognitive task analysis (CTA) of the performance of experienced and less experienced paramedics as they handled simulated emergency response scenarios. The purpose of the research was to understand the cognitive strategies used by paramedics—and by the emergency medical system more generally—to adapt to novel challenges.

Participating paramedics in the Smith et al. (2013) study handled two emergency scenarios. The scenarios were based on actual cases and were developed with the help of subject matter experts and reviewed by further experts before being presented to the participants. In the first scenario, a middle-aged man presented with chest pain, suggesting an initial diagnosis of a heart attack, but the eventual diagnosis was a pulmonary embolism (blockage in an artery in the lung) rather than a heart attack. Each participant had to detect the cues for the pulmonary embolism and revise their initial diagnosis accordingly. In the second scenario, two shooting victims had to be monitored and treated simultaneously. One patient had a head wound, was unresponsive, and slowly deteriorating, whereas the other patient had a chest wound, was responsive, but indications were that he might suddenly deteriorate with a tension pneumothorax (introduction of air into the pleural space that impedes return of blood to the heart). Each participant had to detect the more immediate risk presented by the second patient, and arrange an appropriate delegation of care between himself and a less-qualified EMT-basic level partner, given the balance of risks.

The methods that Smith et al. (2013) used to elicit the paramedics' problem solving exemplify the approach to CTA advocated and practiced by Woods and colleagues since the early 1980s. First, the paramedics' cognitive strategies were investigated by observing domain practitioners handling professionally authentic situations. Second, rather than using open-ended field observation, where complex situations may not happened often enough and predictably enough to be analysed efficiently, the researchers used ‘mixed-fidelity simulation’ or ‘staged worlds’ in which carefully selected complex situations were partially reconstructed and presented to practitioners. In the Smith et al. example, patients were simulated computationally, whereas the participant’s EMT-basic level partner was acted by a member of the research team. Third, the researchers investigated situations that were complex and that involved cognitive challenges for the participants, rather than situations that were routine for the participants.

Similarly, the methods that Smith et al. (2013) used to analyse the records of paramedics’ problem solving are typical of CTA at its best. Smith et al. sought evidence for activities that might distinguish the problem solving processes of the experienced vs. less experienced paramedics. They therefore used process tracing, “a technique that uses iterative passes through the data to capture domain-specific and progressively more abstract patterns of cognitive performance” (p. 372). The audiovisual records were transcribed, and analysed in a series of passes that moved from constructing a coherent account of the basic activities as they unfolded over time, to identifying high level patterns of reasoning and decision making that typify different levels of expertise. The analyses involved a process of abstraction similar to that used in the human performance model of Hollnagel et al. (1981)..

What the Smith et al. (2013) example does not show is the intimate connection between cognitive task *analysis* and cognitive task *design* (CTD) that is also a core feature of CSE and the work of Woods and his colleagues. As Woods (1998) has memorably noted in the title of one of his papers, “designs are hypotheses about how artifacts shape cognition and collaboration” (p. 168).

In addition, although it presents generalisations about expertise, the Smith et al. example has a practical purpose and does not proceed to infer or invoke laws. In more recent work, Woods and colleagues have encapsulated regularities in how joint cognitive systems work into a series of laws, described below.

X.4 Theoretical Descriptions of Joint Cognitive Systems at Work

A key question for those analyzing cognitive work is where the more formal or theoretical language comes from that is the result of the CTA or the motivation for the CTD. Specifically, what is the source of the competence description at the top of Figure 2?

In the original Hollnagel et al. (1981) report of the human performance model, the question driving the investigation was how best to train human operators to control NPPs. Summaries reflecting analyses at different levels of the performance analysis diagram supported different kinds of training activity. For example, aggregated performance data that preserved details of individual or team cognitive work in context—including data representations informed by formal concepts such as switches between strategies—supported training in the form of direct operator debriefing. In contrast, tools and concepts that Hollnagel et al. used to move from domain-specific to domain-independent descriptions included analytic templates such as the “human malfunction” taxonomy or the skills-rules-knowledge (SRK) framework, the decision ladder, and variants of them adapted to the needs of the research. Summaries using the latter tools and concepts supported evaluation of the overall effectiveness of training programs, rather than the specification of training content.

The specific formal language or theoretical framework that might occupy the competence description at the top of Figure 2 will depend of course on the specific question that the analyst is investigating. The theoretical framework could have many origins and could be based in theories of expertise, learning, diagnosis, stability and control, adaptation, or decision making, amongst many others.

Over the years of observing how cognitive work is managed in complex sociotechnical systems undergoing change, and the challenges that people face as partners in joint cognitive systems, Woods and colleagues have developed "laws" that describe how joint cognitive systems function and that account for successes or failures in the interaction between people, technology and work (Hollnagel & Woods, 2005; Woods & Hollnagel, 2006). Decades of research into the impact of new technologies in domains such as power generation, aviation, critical care, and other domains makes it abundantly clear that joint cognitive systems are not always designed in a way that avoids the pitfalls captured in some of the above laws. Therefore an efficient way to investigate the impact of change on cognitive work is to be guided by search for instances where these laws have been respected or violated. In other words, the analyst should be prepared to find instances where the laws are in operation but also prepared to find instances where the relationships described by the laws are present in new, surprising, ways, or are absent.

Hollnagel and Woods (2005) and Woods and Hollnagel (2006) called the above universals *laws that govern joint cognitive systems at work*. They are laws in the sense of being general truths proposed about how joint cognitive systems function that have been found to hold over a wide variety of domains. As the authors note, however, the laws unfortunately appear to be "optional" in terms of whether designers respect them, yet the consequences of not respecting them are inevitable. Specifically, evidence suggests that if the laws are not respected when new technology is introduced into a work system, new complexities are introduced and operators do not have the tools to cope with those complexities

Woods and Hollnagel (2006) proposed five general categories of the laws that govern joint cognitive systems at work. The *Laws of Adaptation* cover phenomena associated with "how cognitive systems adapt to the potential for surprise in the world of work". The *Laws of Models* cover phenomena associated with how through models (mental or otherwise) based on the past, people project into the future. The *Laws of Collaboration* cover phenomena associated with the fact that cognitive work is distributed over multiple agents and artifacts, and so is inherently social and distributed in nature. The *Laws of Responsibility* cover phenomena associated with the fact that people modify artifacts to better achieve their own goals. Finally, *Norbert's Contrast of People and Computers* (named for Norbert Weiner) expresses the fundamental truth that "artificial agents are literal minded and disconnected from the world while human agents are context sensitive and have a stake in outcomes" (Woods & Hollnagel, 2006; p. 158).

Each category of the laws that govern joint cognitive systems at work contains several more specific laws that are also generalisations about the effective or ineffective functioning of joint cognitive systems. There are too many specific laws to detail here, and they are described in more detail in Woods and Hollnagel (2006). However, some examples of the Laws of Adaptation should provide the flavor of the more specific laws and give an idea of how they might be used "top down" during an analysis of cognitive work, either as hypotheses about factors shaping cognitive work (left side of Figure 2), or as principles that must be respected when designing new cognitive work tasks or tools (right side of Figure 2).

One of the Laws of Adaptation is *context-conditioned variability*, or "the ability to adapt behavior in changing circumstances to pursue goals" (Woods & Hollnagel, 2006; p. 171). When studying people's response to disturbances or changes in their work, an analyst's awareness of this law would focus their attention on changes or constancies in the kind of behavioural routines in evidence, constraints being respected, and apparent goals being pursued. Experienced operators might be quicker to recognize the change in circumstances, and quicker to find new behavioural routines that will nonetheless respect constraints and satisfy the original goals. If an analyst is aware of the regularity expressed in the concept of context-conditioned variability, then they may be quicker to recognize its absence or presence in the behavior of the operators being observed.

A further Law of Adaptation is the *Law of Stretched Systems*, which is the idea that "every system is stretched to operate at its capacity … as soon as there is some improvement, some new technology, we exploit it to achieve a new intensity and a new tempo of activity" (Woods & Hollnagel, 2006; p. 171). Awareness of this law would focus the analyst's attention not just to anticipated uses of a new technology but also to the emergence of unanticipated uses of it, potentially directed at goals other than those for which the technology was developed, and it would focus the analyst's attention on investigating the consequences of those unanticipated uses more broadly.

The benefit of laws of course is that they provide a basis for interpretation, generalization and prediction. They are therefore an integral part of CTA and CTD. It is clear from the above high-level description that the laws all refer to some aspect of joint cognitive systems *at work*, in a work domain or environment.

X.7 Conclusions

In this chapter I have provided a brief sketch of how cognitive work is conceptualized and analysed in the CSE work of Woods and his colleagues. I have also briefly related Woods' approach to other communities of practice and other approaches, such as CWA and other forms of CTA, while noting that they all spring from a similar history and set of motivations. Despite this, I have only skimmed the surface of the approach that Woods and colleagues take to the study of cognitive work.

The performance analysis framework that covers both CTA and CTD is important and it deserves to sit at the core of many future investigations of cognitive work and many reviews of its methods. At the core of the framework is the role of theory – theory development, theory testing, and theory use – and it can be seen how theory that is developed in one domain of work or for one set of problems may become a powerful tool for the analyst when starting to understand cognitive work in a novel domain, or starting to investigate a novel set of problems. The set of generalisations represented in Woods' laws that govern joint cognitive work provide such theoretical leverage.

Finally, an understanding of the cognitive systems triad is essential to understanding the value of understanding cognitive work through staged worlds, alongside other methods. The cognitive systems triad emphasizes that cognitive work in a complex domain must be studied in the process of engaging with that domain, rather than separately from it. From this follows the importance of naturalistic field studies and, particularly, of staged worlds that have been constructed to provide a more efficient way of exposing authentic cognitive work.

Readers should refer to Woods and Hollnagel (2006) for an integrated description and further development of many of the themes touched on in this chapter. Many of the more informative examples and expositions are in book chapters, some of which are referenced in this chapter.

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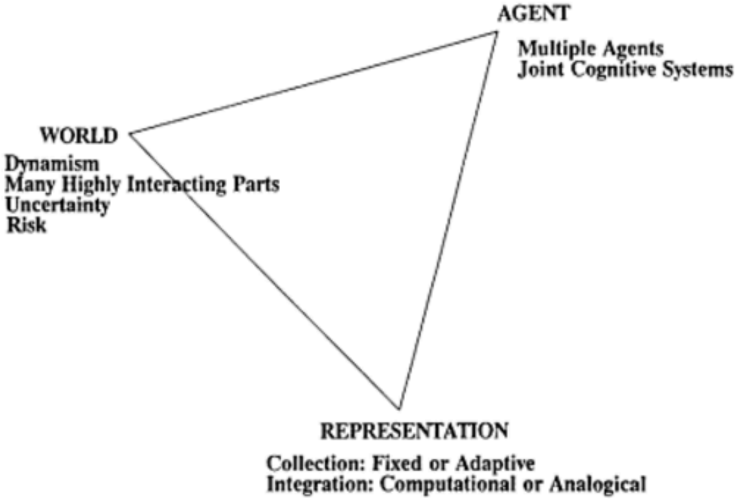
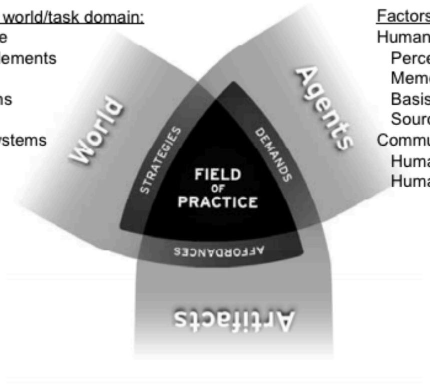
List of figures

Figure 1. Two versions of the cognitive systems triad showing factors shaping cognitive work. Left diagram is an early version (Woods, 1988) and right diagram is a more recent version (Woods, Tinapple, Roesler, & Feil, 2002). Left diagram is republished with permission from Taylor and Francis (CRC), from L. Goodstein, H. B. Andersen, & S. E. Olsen (Eds.), *Tasks, errors, and mental models*. Bristol, PA: Taylor & Francis, Inc., Copyright © 1988; permission conveyed through Copyright Clearance Center, Inc. Right diagram is republished with permission from the author.

Figure 2. Levels of analysis of human performance, adapted from Hollnagel et al. (1981) and Woods and Hollnagel (2006). Adapted with permission from D. D. Woods and E. Hollnagel, *Joint cognitive systems: Patterns in cognitive systems engineering*. Boca Raton, FL: Boca Raton, FL: CRC Press, Copyright © 2006; permission conveyed through Copyright Clearance Center.

Figure 1





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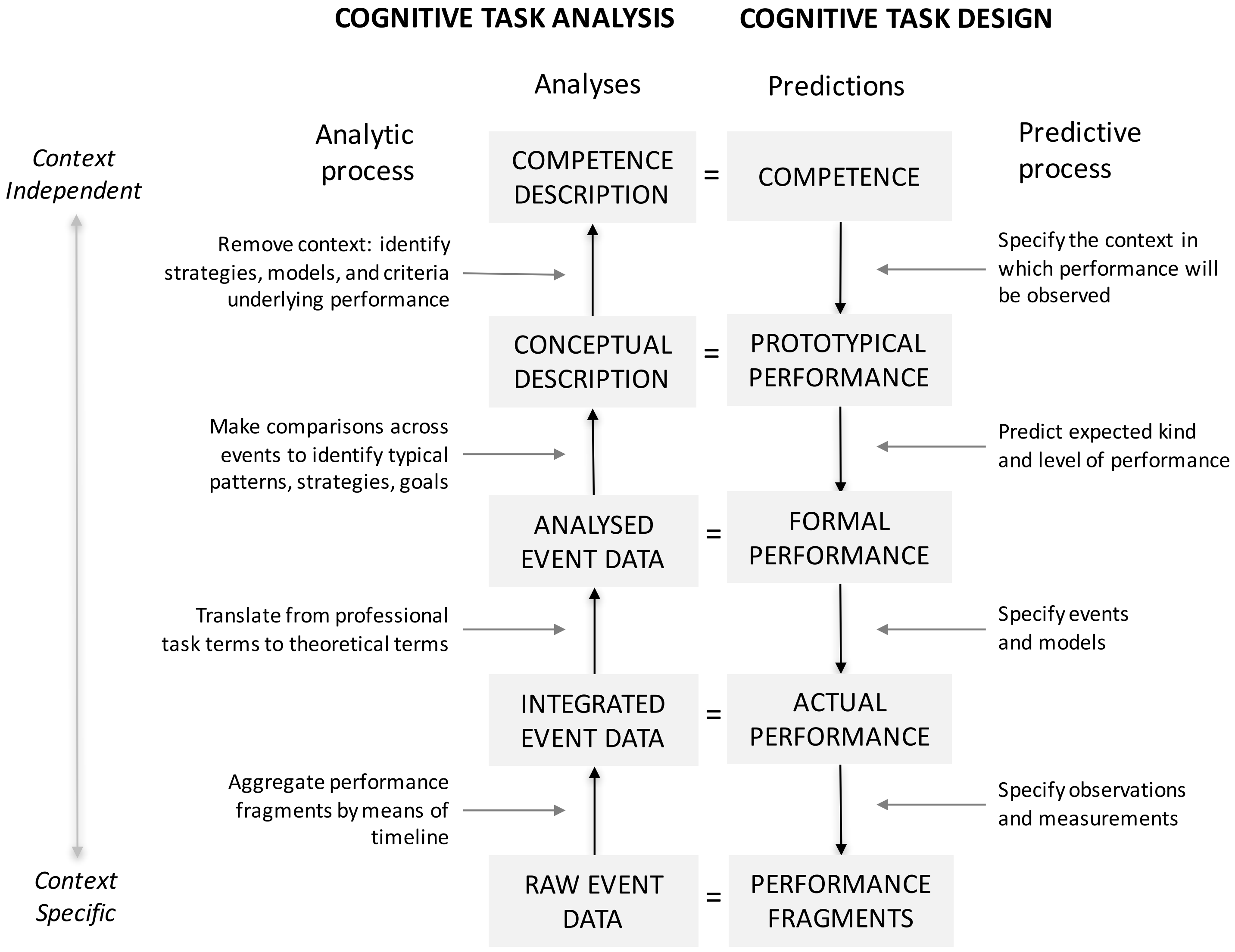
Factors in the external world/task domain:
- Goal-means structure
- Complexity of task elements
- Hazards
- Constraints on actions
- Temporal dynamics
- Coupling between systems
- Uncertainty and risk

Factors with human and machine agents:
- Human Information Processing
  - Perceptual characteristics
  - Memory and attention characteristics
  - Basis for skill and expertise
  - Sources of error
- Communication and coordination
  - Human-Human
  - Human-Intelligent system

Factors with artifacts and information representations:
- Mapping to domain goal-means structure
- Visual Form
- Directability / Gulf of execution
- Observability / Gulf of evaluation

Figure 2


COGNITIVE TASK ANALYSIS
COGNITIVE TASK DESIGN
Analyses
Predictions
Analytic process
Predictive process
Context Independent
Context Specific
COMPETENCE DESCRIPTION
=
COMPETENCE
Remove context: identify strategies, models, and criteria underlying performance
Specify the context in which performance will be observed
CONCEPTUAL DESCRIPTION
=
PROTOTYPICAL PERFORMANCE
Make comparisons across events to identify typical patterns, strategies, goals
Predict expected kind and level of performance
ANALYSED EVENT DATA
=
FORMAL PERFORMANCE
Translate from professional task terms to theoretical terms
Specify events and models
INTEGRATED EVENT DATA
=
ACTUAL PERFORMANCE
Aggregate performance fragments by means of timeline
Specify observations and measurements
RAW EVENT DATA
=
PERFORMANCE FRAGMENTS

Indexing terms

Abstraction
Actual performance
Adaptation
Agents
Analysed event data
Apparent realism or face validity
Artifacts
Cognitive task analysis (CTA)
Cognitive task design (CTD)
Cognitive systems triad
Cognitive systems engineering (CSE)
Cognitive work analysis (CWA)
Collaboration
Competence
Competence description
Conceptual description
Context-conditioned variability
Context free description
Context independent account
Critical decision method
Decision ladder
Ecological Interface design (EID)
Emergent behavior
Face validity
Field observation
Formal performance
Generalisation
Human performance analysis
Instantiation
Integrated event data
Joint cognitive system
Knowledge-based behavior
Laws that govern joint cognitive systems at work
Laws of adaptation
Laws of models
Laws of collaboration
Laws of responsibility
Law of stretched systems
Literal minded
MacSHAPA
Meaningfulness
Mental model
Mixed fidelity simulation
Natural history methods
Naturalistic observation
Norbert's contrast of people and computers
Nuclear power plant
Observation problem in psychology

Perceptual cycle
Performance fragments
Process tracing
Prototypical performance
Response complexity
Raw event data
Risoe National Laboratory
Skills-Rules-Knowledge (SRK) framework
Sociotechnical system
Spartan laboratory experiments
Specificity
Staged worlds
Think aloud protocols
Top-down analysis
Three-Mile Island accident
Unanticipated uses
Work domain analysis (WDA)

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