This is a draft of a chapter that has been accepted for publication by Oxford University Press in the forthcoming book "Oxford Handbook of Expertise: Research & Application," edited by P. Ward, J. M. Schraagen, J. Gore & E. Roth, due for publication in 2019.

Macrocognitive Models of Expertise

Robert J B Hutton

Keywords: macrocognition; cognitive work; models; sensemaking; decision making; adaptation; complexity; flexecution

Introduction

Macrocognition is the adaptation of cognition to the complexities of real world work. Macrocognitive models were developed in order to explore the boundaries of microcognitive models, addressing the cognitive phenomena of dynamic interactions of people, work, and the environment in which work takes place. Of particular relevance to the focus of this handbook, macrocognitive models tend to be models of expert performance, given that they are based on empirical evidence from skilful professionals in their work contexts.

This chapter is intended to provide a brief understanding of macrocognition, some of its theoretical underpinnings, and some examples of macrocognitive models. It is not intended to be a comprehensive resource representing all the macrocognitive models that have been developed. The interested reader is encouraged to read Schraagen, Klein and Hoffman (2008), who provide an overview of the concept as an introduction to a broader set of relevant chapters, and Hoffman and McNeese (2009) who provide an excellent historical perspective.

This chapter addresses the following:

- What do we mean by macrocognition?
- Theoretical foundations and influences
- Methods used to study and develop these models
- A few exemplar models
- Future challenges and forward thinking

What is Macrocognition?

Macrocognitive models have emerged in the most part due to efforts to understand and remedy applied problems. Models from cognitive psychology have not provided sufficient support to understanding and solving the challenges of real world work, and thus macrocognitive models have emerged to fill that gap. Models developed from the controlled contexts of experimental psychology have been termed *microcognitive* models in order to distinguish the levels of analysis represented by the macro- micro- terminology. Cacciabue and Hollnagel (1995) summarized the distinction in the following way:

> "Macro-cognition refers to the study of the role of cognition in realistic tasks, that is in interacting with the environment. Macro-cognition only rarely looks at phenomena that take place exclusively within the human mind or without overt interaction. It is thus more concerned with human performance under actual working conditions than with controlled experiments." (pp.57-58).

The emerging definition of macrocognition acknowledges two key elements (Schraagen, Klein & Hoffman, 2008):

1. Cognitive work can only be understood through study at a number of levels or perspectives
2. Information processing models (exemplified by experimental cognitive psychological models, e.g., Wickens et al., 2015) provide an incomplete and incorrect understanding of cognitive work.

Klein, Klein, and Klein (2000) suggested that the term macrocognition be used to "designate the more complex cognitive functions. These functions would include decision-making, situation awareness, planning, problem detection, option generation, mental simulation, attention management, uncertainty management, expertise and so forth." (Klein, Klein, & Klein , 2000, p.173).

Klein, Ross, Moon, et al.'s (2003) offer a contrast between microcognition and macrocognition in order to emphasize the complementarity of the two levels of description: "These types of functions—detecting problems, managing uncertainty, and so forth—are not usually studied in laboratory settings. To some extent, they are emergent phenomena. In addition to describing these types of phenomena on a macrocognitive level, we can also dscribe them on a microcognitive level. The two types of description are complementary. Each serves its own purpose, and together they might provide a broader and more comprehensive view than either by itself. We do not suggest that the investigation of macrocognitive phenomena will supercede or diminish the importance of microcognition work—just that we need research to better understand macrocognitive functions in order to improve cognitive engineering." (p.81).

These authors characterized the key challenges associated with cognitive work which occurs in naturalistic settings but not laboratory studies as:

- Decisions are typically complex, often involving data overload
- Decision are often made under time pressure and involve high stakes and high risk
- Research participants are domain practitioners rather than college students
- Goals are sometimes ill-defined, and multiple goals often conflict
- Decisions must be made under conditions in which few things can be controlled or manipulated, indeed many key variables and their interactions are not even fully understood.

They identified the limitations of a purely microcognitive perspective with respect to the potential distortions that could result from studying cognitive processes in isolation from one another and in isolation from the contexts in which the practitioners apply those processes to achieve work or performance objectives.

The term macrocognition has also been used specifically to describe cognition at the level of team performance, where the *macro*- refers to cognition amongst multiple actors (Fiore et al., 2010; Warner, Letsky & Cowan, 2005; Letsky et al., 2008). This use of this term is certainly relevant in the context of cognition in naturalistic environments where multiple players often characterize the work context. Understanding the challenge of cognitive performance in multiple-actor contexts (including intelligent/computational agents) is beyond the scope of this chapter, however it should be noted that macrocognition is not merely the purview of team performance. The models described in this chapter focus primarily on individual decision makers.

Macrocognitive models provide attempts to describe and understand the challenging aspects of purposeful cognitive performance in the dynamic flow of complex and uncertain situations. The models acknowledge the antecedents of problem solving and decision making, the meaning and implications of situational factors, and they recognize the value and impact of those solutions and decisions on subsequent performance. They are arguably ecological models in the Gibsonian/Brunswikian sense (Gibson, 1979/2014; Brunwsik, 1956) in that they often represent cycles of behavior, rather than mere input-output relationships. They are intended to provide a view of human performance that acknowledges the messiness of many of the work contexts that have provided data for these models. Hoffman, Norman, and Vagners (2009) defined macrocognition as a process of “adapting cognition to complexity” (p. 87) which describes macrocognition as a dynamic application of thinking to evolving events.

With respect to how we represent macrocognition as a model, this presents a number of challenges. Indeed there are disagreements within the community as to the key characteristics of macrocognitive models and how they are represented. For the purposes of this chapter we recognize that there are both *weak* and *strong* models of macrocognition. These may represent the evolution of macrocognitive models over the past 30 years, where some of the earlier (arguably *weaker*) models represented retrospective, descriptive, causal chain, input-output models that help tell stories, but not make predictions. Some also believe that they oversimplify cause-effect relationships in the cognitive dynamic. Later *strong* models which are represented as closed-loop models, recognize the reciprocity of actor and environment, much like Gibson and Neisser’s views of perception and action (Gibson, 1979/2014; Neisser, 1976) and the dynamics of cognition. They represent sets of processes that are continuous, parallel, highly interacting that represent the dynamics of cognition as a *stream of events*.

Finally, and most importantly for the purposes of the handbook, we must address the role of experience and expertise in the people who are planning, making decisions, making sense of situations, re-planning and so forth in their work contexts. In many cases, models of macrocognition are, by definition, models of expert cognition. Expertise and skilled performance are viewed as the gold standard for cognitive performance and thus many of the models represent expert cognition. The reason that this is important is that experts make sense, decisions, and plans in the context of work-based situations. To do so successfully, they must have developed a refined sense of the cues and factors that contribute to their thinking, and developed sophisticated mental models of how their world works to allow them to understand and predict situations effectively. Macrocognitive models reflect this actor-environment relationship in terms of how experts bring their experience, mental models, and knowledge to bear on complex problems to effect satisfactory outcomes.

Macrocognitive models describe how knowledge and experience contribute to effective adaptation to the complexity of scenarios which impact performance outcomes. This is in contrast to many *traditional* cognitive models which fail to account for these adaptation and complexity challenges because they have been generated based on relative novices working on tasks that are new to them (e.g. tower of Hanoi problem solving, or gamble or choice decision tasks).

Thus far we have only hinted at the focus of macrocognitive models. It should be noted that the variety of macrocognitive models has continued to evolve and grow over the past 30 years, and thus the framework presented in Figure 1 for understanding macrocognition represents only a snapshot. Figure 1 represents one version of the macrocognitive functions and processes as described in Klein et al., (2003), providing the reader with a sense of the language, scope and focus of macrocognitive models.

Figure 1. The macrocognitive "wheel" which effectively provides a list of the various macrocognitive processes and functions. The processes describe how we think, whereas the functions describe what we achieve. (Adapted from Klein et al., 2003; reproduced with permission from G. A. Klein).

The functions represented in Figure 1 are not a comprehensive list, nor is it complete. Iterations of current models are continuously being revised and updated based on new research. Crandall, Klein and Hoffman (2006) provide brief descriptions of each of these functions and processes (pp.137-142). Three example models will be presented in more depth later in the chapter.

Theoretical Foundations

Macrocognition has broadened its scope from an initial focus on decision making, to addressing the span of cognitive performance (for individuals and teams). This means that it is comparing itself with a variety of *traditional* models including decision making, problem solving, memory, attention, levels of processing, learning and transfer. This chapter will focus on three macrocognitive models (recognition-primed decision making; sensemaking; and flexecution) which can be contrasted with *traditional* cognitive psychology models, especially of decision making (classical judgment and decision theorists), comprehension, and problem solving. However, it is difficult to pinpoint specific targets for comparison as macrocognitive models draw different boundaries around the activities and typically incorporate several components of what would traditionally be the realm of a single microcognitive model. The comparisons are therefore not like-for-like as a single macrocognitive model could be reliant on the *building blocks* of multiple microcognitive models. In some cases, because the unit of analysis for macrocognitive models tend to be at the level of *cognitive work* there are rarely close direct corollaries within the cognitive psychology models of the 1970s and 1980s. Klein et al. (2003) described the situation in the following way using the example of the Recognition-Primed Decision model which will be described in more detail next:

> "After considerable research on recognition-primed decision making, we realized that the model was basically a combination of three decision heuristics that had already been well-studied from the microcognition perspective: availability and representativeness to identify the typical course of action, and the simulation heuristic to evaluate the course of action. Therefore, in this case it was possible to trace the macrocognitive phenomenon back to hypothetical microcognitive components. However, several decades of research on the

> availability, representativeness, and simulation heuristics had not led to a discovery of recognitional decision making. That is why we see the macrocognitive functions as emergent. We discover them by investigating cognition in field settings rather than by continually pursuing explanations of lab findings" (p. 82).

On the whole, traditional cognitive models of cognition are fundamentally lacking in accounts of experienced people (but see other chapters in this section, including the chapter on *The Classic Approach*, this volume) who use their domain knowledge and experience to solve real work problems characterized by time pressure, uncertainty, complexity (emergent problems), and a variety of external constraints which impact cognitive performance. The macrocognitive models are derived from studying exactly these kinds of problems, and provide insights into how people achieve effective cognitive performance under *messy* conditions.

Methodological Foundations

In addition to the theoretical underpinnings, it is also useful to understand the methodological approaches that have provided the predominant source of data for the development of macrocognitive models. Fundamentally, the methods used are cognitive field research methods. In order to understand the influences of experience and expertise and of environmental factors on human cognition in real world contexts, researchers have had to develop and refine methods for studying cognition outside the laboratory. These are broadly described as cognitive task analysis (CTA) methods (see Hoffman & Militello, 2009 for an excellent treatment of the methodological underpinnings of CTA).

Data gathering to understand the nature of participant experience, knowledge and expertise, and to understand the environmental opportunities and constraints typically involve a triangulation of methods including:

1. Examination of documentation of the work, including training manuals, procedure guides, doctrine and policies, and so forth.
2. Observation of workers in action, working with tools and artefacts, other people, and struggling with the realities of complex work
3. *Think aloud* protocols from workers as they are doing their work. (see chapter on a *Historical Perspective on Introspection*, this volume)
4. Semi-structured interviews with workers about the challenges and complexities of their work contexts, with a particular emphasis on *tough cases*. (see chapter on *Incident-based Methods*, this volume)
5. Modelling of work practice, with review and feedback by a variety of workers and subject matter experts. (see chapters on *Hierarchical Task Analysis*, *Cognitive Work Analysis*, and *Knowledge Capture*, this volume)

The macrocognitive model development process has often been instigated by a practical, applied question that researchers have been unable to answer based on existing cognitive models, concepts or theories. These applied questions have stimulated enquiry using a variety of the methods identified above (e.g., see Crandall, Klein, & Hoffman, 2006 for one useful guide to conducting CTA; for an overview of the full breadth of other cognitive engineering methods and their applications, see also Lee & Kirlik, 2013). A review of the large variety of methods that have contributed evidence to the development of these models is beyond the scope of this chapter, but the reader is encouraged to look at Schraagen, Chipman, and Shalin (2000) and Hoffman and Militello (2009) for reviews of the various perspectives, both theoretical and methodological, that have made valuable contributions. The next section provides three examples of macrocognitive models in order to provide illustrations of the character, content and focus of these models.

Three Macrocognitive Models

Three models will be described here for purposes of illustration. These models represent examples of how the concept of macrocognition has evolved over time. The first model is Klein's Recognition-Primed Decision (RPD) model (Klein, et al., 1986; Klein, 1997; 1999). The second is a model that complements one aspect of the RPD model which represents a *diagnosis* loop that has since been elaborated into the Data-Frame model of *Sensemaking* (Sieck et al., 2007; Klein, Phillips, Rall, & Peluso, 2007). The final model is the *Flexecution* model of adaptive replanning (Klein, 2007a; 2007b).

Recognition-Primed Decision (RPD) Model

The RPD model is probably the oldest and best known model that has emerged from the Naturalistic Decision Making community, a community of practice who have pioneered the macrocognitive perspective. First described by Klein, Calderwood, and Clinton-Cirocco (1986), the purpose of the study that led to the development of the model was to examine the ways decisions are made by highly proficient personnel, under conditions of extreme time pressure, and where the consequences of the decisions could affect lives and property. The study was conducted on behalf of the US Army who wanted a better explanation of how military commanders could make effective decisions given the characteristics of operations including time pressure, information uncertainty, and high stakes. The firefighting domain was chosen as a surrogate for military decision making given the difficulty of observing military commanders in action. Observations and interviews were conducted with experienced Fire Ground Commanders (FGCs) who are responsible for allocating personnel and resources at the scene of a fire. The interviews focused on the work challenges, and particularly tough cases where the FGC's expertise was challenged.

The original intent of Klein's study was to understand how FGCs identified options and selected courses of action from amongst those options. However, based on an analysis of

156 decision points, the researchers found that only 12% of the decisions discussed included any sort of option comparison, but that 80% of the examples were resolved based on matching current experienced situations to similar situations from past experience. The course of action (COA) that worked before was implemented again (Klein et al., 1988). This study provided the initial evidence for the development of a recognition-primed strategy for effective decision making that contradicted many of the classical normative rational decision models that had been proposed to date (e.g. see Hastie & Dawes, 2001/2010).

Evidence for the RPD Model

There is a growing amount of empirical evidence that supports RPD’s descriptive account of the way that experienced people make decisions. Although challenging to test empirically, there are some assertions upon which RPD relies and for which empirical support has been found:

1. People can use experience to generate a plausible option as the first one they consider (Klein, Wolf, Militello, & Zsambok, 1995)
2. Time pressure need not cripple experienced decision makers (Calderwood, Klein & Crandall, 1988)
3. Experienced decision makers can adopt a course of action without comparing and contrasting possible courses of action (Kaempf, Klein, Thordsen, & Wolf, 1996; Randel, Pugh, Reed, Schuler, & Wyman, 1994; Mosier, 1991; Pascual & Henderson, 1997; Driskell, Salas & Hall, 1994).

The RPD Model

The RPD model is illustrated in Figure 2. It was developed to describe and explain how experienced workers made effective decisions (i.e. the outcome was satisfactory in the context) using their knowledge and experience. Figure 2 presents three variations of the RPD model.

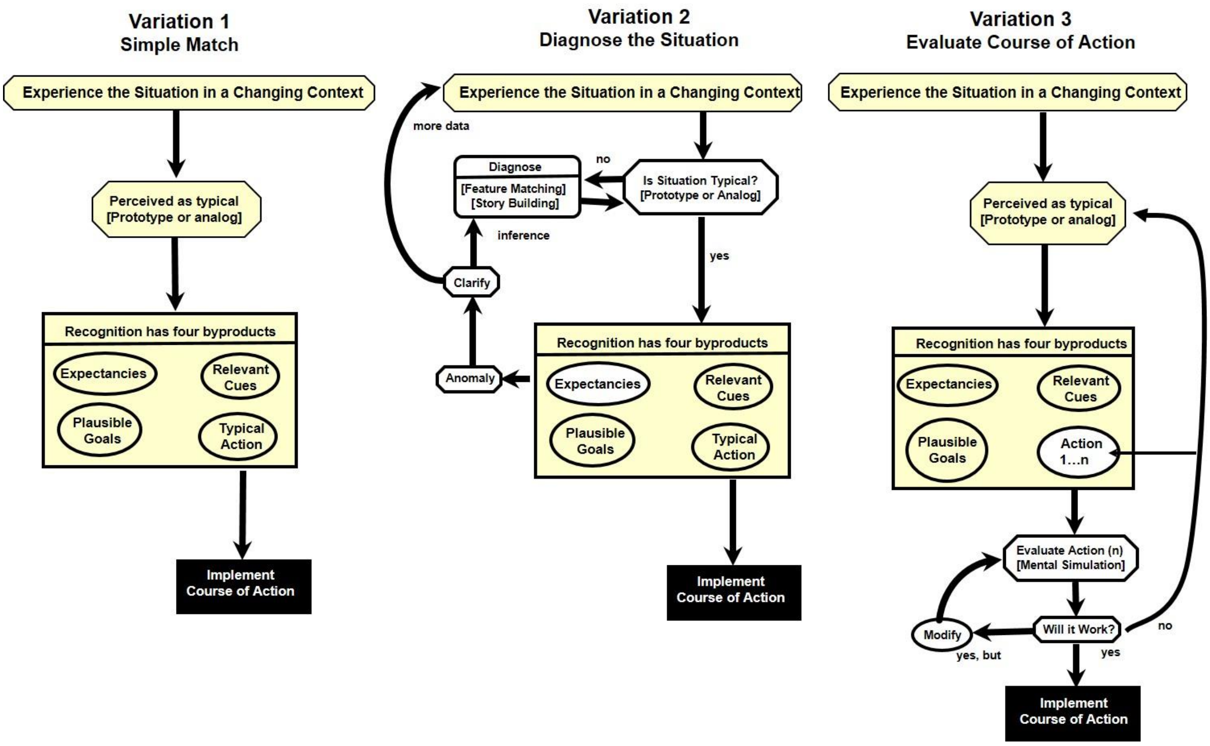

Figure 2. The three level model of Recognition-Primed Decision making (from Klein, 1997; reproduced with permission from G. A. Klein).

Simple Match. In the left-hand panel of Figure 2, the *Simple Match* version of RPD is presented, which is akin to a simple pattern matching strategy or heuristic. The middle panel represents the *Diagnosis* variation which is triggered by the detection of an anomaly in the situation compared to previous experiences, often a violation of expected cues, patterns or trajectory of a situation.

Diagnose Situation. This *Diagnosis* variation of the RPD model describes a situation where a simple match is not identified or is called into question because the situation assessment is not clear or an *anomaly* has been detected with respect to violated expectations about the situation. This variation of the RPD model has since been further developed in the form of the Data-Frame sensemaking model which is described later in this chapter.

Evaluate Course of Action (COA). The final panel represents the *COA Evaluation* variation. This is an instance where a situation is recognized as typical, eliciting an initial candidate course of action. However, on initial consideration of the preferred course of action a potential anomaly occurs requiring the COA to be evaluated further. This analysis of the COA is conducted by a mental simulation whereby the decision maker conducts a mental walkthrough of how the candidate COA might play out given the current situation and the decision maker's mental models of situational factors and dynamics from experience. If the COA is considered workable, it might be implemented as is. However, if a deviation or anomaly is detected during the mental simulation, the COA might be tweaked or the decision maker's understanding of the situation may be sufficiently altered to warrant a different assessment and thus a different candidate COA. This process is described more fully in Klein and Crandall's model of mental simulation (Klein & Crandall, 1995).

The first variation of the RPD model has more recently been described in the context of *intuitive* decision making because it describes how people with expertise leverage their tacit knowledge and perceptual skills to make effective decisions without apparent conscious deliberation, hence appearing to use their *gut* or intuition (Klein, 1999; 2004). Kahneman and Klein (2009) provide a compelling description of the conditions required for developing expertise and the strengths and limitations of intuition in different decision making contexts based on their different perspectives on skilled decision making.

The RPD model is often mistaken to be merely a pattern matching process for decision making using implicit production rules: if situation X, then course of action Y. Although this does describe the simple match version of RPD there are also nuances in the other variations of the model that describe more conscious analytical processes for understanding anomalies and violated expectancies. RPD is not solely an automatic pattern matching process. The full model (including the variants described above) incorporate analytical resources and deliberation. However, the key distinction from deliberation in the rational models, and one of the key insights of the RPD model, is that the analyses are of the situations, not alternative courses of action. In addition, those deliberations occur serially rather than in parallel, against a criterion of satisficing as opposed to optimizing (c.f. Simon, 1972; Kahneman & Klein, 2009).

The RPD model presents an empirically grounded description of rapid decision making when deliberate comparison of COAs is impractical and/or inappropriate. Hammond (1988) posited the cognitive continuum theory to address a spectrum of judgment and decision making from intuitive to analytical. More recently this has been characterized by Stanovich and West (2000), and popularized by Kahneman (2011) as System 1 and System 2, where System 1 refers to models like the first variant of the RPD model (simple match; intuitive), and System 2 refers to the more deliberate analytical models (e.g., Kahneman, 2011). The RPD model has characteristics of both System 1 (RPD Variation 1) and System 2 thinking (RPD Variations 2 and 3) (Kahneman & Klein, 2009).

Limitations

The RPD model is not without its critics, and there are doubtless aspects of the model that could be expanded upon, amended or expanded. The second variation *Diagnose Situation* loop (Figure 2) was added to the RPD model subsequent to its original description, and this chapter will make the further assertion that the Data-Frame model of sensemaking takes this elaboration a step further (although this link has not previously been made explicit). Klein also suggests that processes for option identification or option generation might be aspects that are still missing from the current model (Klein & Wolf, 1998).

It should also be noted that this is a model of expert decision making, requiring knowledge and experience and a repertoire of situation models in order to apply what has also been referred to as the recognitional heuristic approach to decision making. In truly novel situations RPD potentially breaks down, however, research on experts has illustrated that they are still able to generate workable solutions even in the face of novelty (for a review, see Ward, Gore, Hutton, Conway, & Hoffman, 2018), suggesting that there is more to expert decision making than is described in the RPD model (this challenge rests on the definition of novelty and whether the situation falls within the domain of expertise; the notion of adaptive expertise is also explored further in, see chapters on *Cognitive Systems Engineering; Adaptive Expertise*; and *The Future of Expertise,* this volume).

Furthermore, it could be argued that a more comprehensive model of cognition could have been developed based on an integration of a number of macrocognitive models with the RPD as the core framework on which the additional processes hang. This is also arguably a limitation of the RPD model and the macrocognitive models more broadly, that there is a gap with respect to a more coherent overarching theoretical treatment of macrocognitive phenomena. We will revisit this issue in the final section of this chapter when we examine a more recent effort to consolidate across the macrocognitive landscape into a more coherent and integrated perspective which is intended to provide a macrocognitive model of cognitive work more broadly.

Applications

The recognition that RPD is actually broader than a model of decision making only, and more broadly as a model of *cognitive work*, has been evident in its application in a variety of what are referred to as *decision-centered* approaches to supporting improved decision/cognitive performance (Klein, 1993). This is evidently true based on the implicit conception in the Naturalistic Decision Making (NDM) community that decision making is part of a cyclical perception-decision-action cycle rather than merely a choice point. However, human factors applications of RPD theory have inevitably strayed into decision support and cognitive work support through a broad variety of applications including: visualization, support to situation assessment and situation awareness development, maintenance and recovery, training in situational dynamics and building better mental models.

For example, the US military (US Army and US Marine Corps) revised their military decision making, planning and command and control doctrines to recognize the role of rapid, *intuitive* decision making processes, particularly in crisis or time pressured situations. Various fire services (e.g. US, UK, & Netherlands) have adopted rapid decision making as part of their incident command doctrine and processes, making it an explicit part of training curricula. A number of decision-centered training programs has been developed and tested utilizing implications from the RPD model to focus training on decision making performance (see Phillips, Klein & Sieck, 2004; Klein, 2004). With regard to designing engineered systems, decision-centered design (DCD; Hutton, Miller & Thordsen, 2003) adopts methods and models for requirements capture and early concept design that are grounded in an RPD understanding of decision making and how it should be supported by technological applications. Fundamentally, engineered designs should rely on a clear understanding of the cognitive work that needs to be supported. Inevitably RPD, along with other macrocognitive models, provides a way of describing and understanding the key decision requirements and more broadly the cognitive work requirements.

Data-Frame Model of Sensemaking

The Data-Frame (DF) model of sensemaking represents an evolution in thinking from the RPD model as described earlier. It was designed partly to unpack the *Diagnosis* loop of the RPD model which provided only *story-building* and *pattern matching* as processes and strategies for resolving anomalies in understanding evolving situations. The DF model also emerged as a natural progression from exploring commitments to a course of action to elaborating the role of situation understanding. It also satisfied the discovery that many of the *decisions* that were being unearthed by NDM researchers were actually related to assessments rather than courses of action.

Much had been written about the role of situation awareness in human-system performance and the role of assessment of ongoing situations (Endsley, 1995). The DF model of sensemaking was developed to address the cognitive activity that resulted from the emergence of a surprise or anomaly in the decision maker's understanding of the current situation. It was not originally intended to describe how people make sense of ongoing situations that are evolving as expected, or in normal circumstances. The critical driver for the DF model was the response to a sudden realization that what the decision maker thought was happening in the world was actually not the case. No psychological models previously addressed this process of making sense of a situation following a surprise. It is easy to see the progression from the RPD model where an anomaly triggers the *Diagnosis* loop of the model. However, in order to provide the theoretical challenge with appropriate attention and focus, the DF model was developed independently of the RPD model.

Other theoretical treatments of sensemaking exist, most notably Karl Weick's work on organizational sensemaking (1993; 1995). Weick's work focuses on a larger scale of sensemaking in organizations and is mostly used in the context of post-hoc explanations of significant events (e.g. the Mann Gulch disaster, Weick, 1993). The focus of the DF model is on individual sensemaking, although further elaborations have been suggested with respect to the coordination of sensemaking across a team (Klein, Wiggins, & Dominguez, 2010; Hutton et al., 2012). The next section describes the DF model of sensemaking.

The Data-Frame Model

For a detailed description of the DF model of sensemaking, the reader is pointed to Sieck et al. (2007) and Klein, Phillips, Rall, and Peluso (1997). Figure 3 presents the DF model which depicts four core aspects, the data-frame relationship, a *questioning* the frame process, an *elaboration* cycle, and a *re-framing* cycle. Sensemaking is defined as the deliberate effort to understand events and is typically triggered by unexpected changes or surprises that make us doubt our prior understanding. Sensemaking as a process serves several cognitive functions. It supports our ability to detect problems and to focus attention on problematic features of a situation. It also supports making new discoveries and generating insights. It provides us with a way to form explanations about how the current situation came about, but also to anticipate how the situation will evolve in the future. It supports the identification of levers for action by helping to identify the critical causal and influential factors in a situation. Sensemaking helps identify critical relationships between cues and factors that support our explanations and expectancies. Finally, sensemaking enables problem identification (i.e. diagnosis) that supports our understanding of the critical cues and factors that might suggest a solution strategy.

Figure 3 illustrates the key aspects of how the sensemaking process works. The sensemaking process describes a data-frame relationship which provides an initial account that people generate to explain events based on the current data (bottom-up) in conjunction with some organizing frame (top-down). It then supports the elaboration of that account in terms of adding detail, accounting for more information available about the situation, and suggesting additional aspects of the situation based on the current frame. When faced with inconsistent data, the sensemaking process requires a questioning process that allows a person to challenge the current assessment. However, there is a tendency to fixate on the initial account for which the model of the sensemaking process must take account. The process supports the discovery of inadequacies in the initial account which must then be addressed with respect to comparisons of alternative accounts, and/or re-framing of the initial account, replacing it with an alternative that is either recognized from previous experience or must be deliberately constructed. This is a description of the sensemaking process at a high level based on evidence from a variety of examples from real world decision contexts including military operations, medical scenarios, business and firefighting examples (Sieck et al., 2007).

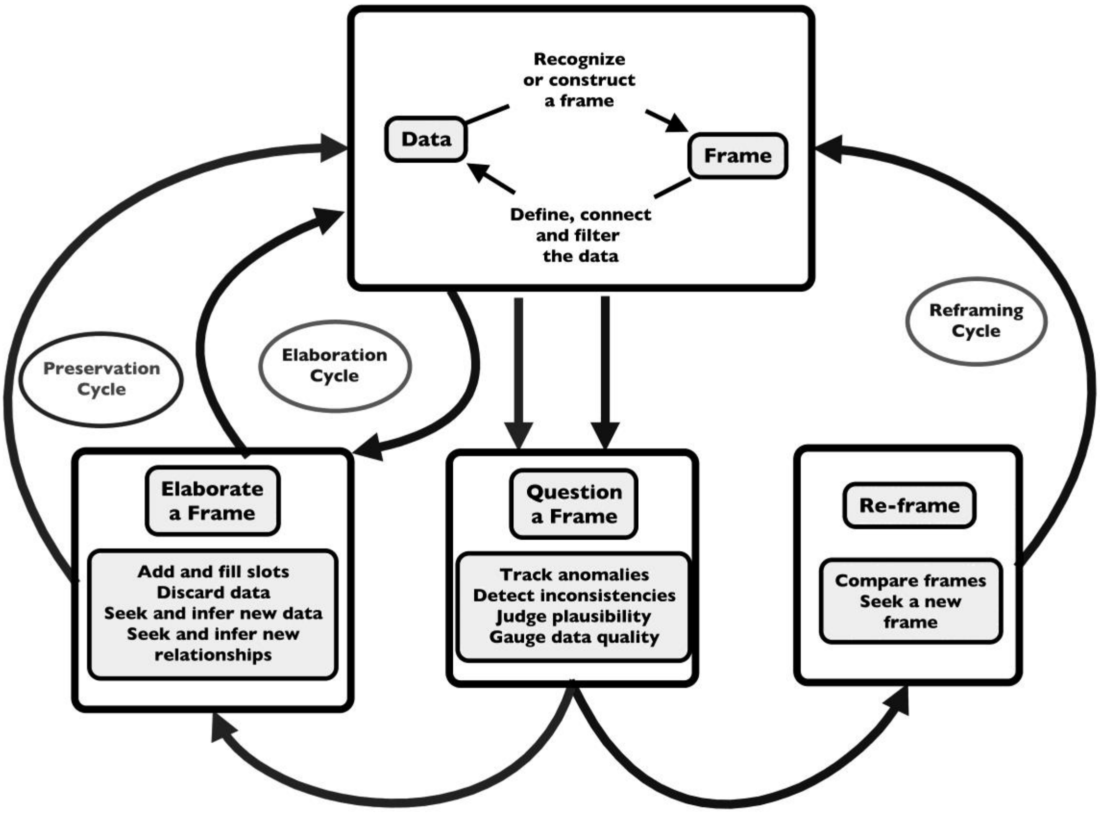

Figure 3. The Data-Frame model of sensemaking (Adapted from Klein et al., 2007; reproduced with permission from R. R. Hoffman).

The DF model postulates that elements of a situation, based on available data, are explained when they are fitted into a structure that links them to other elements. The concept of a *frame* is used to denote an explanatory structure that defines entities by describing their relationships to other entities. A frame is a structure for accounting for the data as well as guiding the search for more data. The frame could be based on a person's compiled experiences or it could be represented by a narrative or a physical structure, such as a map, that is used to piece together the existing data and provide the connections and relationships between the available data, as well as filling in the gap (inferences) and revealing gaps (future data collection requirements).

Evidence for the Data-Frame Model of Sensemaking

The empirical data which was used to develop this model came primarily from studies in a defense context. Information Operations (IO) officers provide one source of data based on the completion of challenging assessment scenarios which were then used as a basis for CTA activities. Another source of data came from people making *in situ* navigational assessments, particularly in a situation where they were trying to recover from getting lost (Sieck et al., 2007). Finally, a retrospective analysis of a corpus of critical decision data were reviewed in order to identify interviews which focused on challenging decisions relating to assessments of situations and sensemaking, rather than on developing and evaluating course of action option.

The study with IO officers looked at expert/novice differences (Sieck et al., 2007). Officers were presented with a number of situation reports, and supporting materials, relating to complex military scenarios. They were interviewed with respect to their assessments of an evolving situation, about judgments and inferences relating to understanding the current situation, speculations and explanations for events, and the knowledge and previous experiences which supported those inferences, speculations and explanations.

Independent coding of the interview protocols revealed a number of processes and strategies that were used to make sense of the situations, including active exploration of connections between reports (including reports which were included as *noise*). Experts generated more connections between the reports based on richer mental models developed from their experience. Both groups used similar sensemaking strategies, including inferring causes, effects, and their relationships, as well as inferring causes from effects, having an awareness of multiple causes, and identification of instances where the cause resulted in an unexpected effect. Experts were able to identify more associations between multiple causes and effects than novices, and more implications with respect to anticipating events and taking actions to develop their understanding.

Further interviews were conducted with IO officers using interview methods relying on the elicitation of retrospective incidents and generated a number of sensemaking incidents which were analysed in depth (Sieck et al., 2007), contributing to an elaboration of the sensemaking model. Data were also collected relating to the corruption and recovery of sensemaking during real-life navigational experiences of getting lost and *getting found* again, which supported the initial versions of the Data Frame model. Finally, Sieck et al. reviewed archival data from a number of projects to generate further evidence of sensemaking based on CTA interviews of past critical incidents. These data included incident examples from firefighting, neo-natal intensive care nurses, Naval operations room (Combat Information Centre) teams, and a number of small unit Army commanders.

Key Features

The DF model is based on some key assertions relating to the processes of sensemaking.

Reciprocal Data-Frame relationship. Firstly, sensemaking is the process of fitting data into a frame whilst also fitting a frame around the data. It is both a top-down and bottom-up process. This is critical with respect to how the model deviates from other models where there is often an assumption of one-way processing. The data are the interpreted signals of events. Frames are the explanatory structures that account for the data. Sensemaking balances these two entities, neither has primacy.

It's not just connecting the dots. The notion of the *cognitive hierarchy/pyramid* or waterfall models of sensemaking suggest that more data generates information which is transformed into to knowledge, and finally leads to understanding (for example, Army Field Manual 6-0 Mission Command: Command and Control of Army Forces; Appendix B:

Information). This sort of thinking promotes the idea of sensemaking in a military intelligence context as *connecting the dots*, however the DF model highlights the idea that a dot is defined in part by the frame with which the analyst is making sense of the situation. Thus, *connecting the dots* only makes sense in hindsight, because what counts as a dot is often hard to discern in the noise, uncertainty and complexity of real world scenarios (Klein, 20011, ch.12). Data elements are not perfect representations of the world but are constructed. Different people viewing the same events can perceive and recall different things depending on their goals and experiences. The identification of what counts as data depend on the background experience and on the repertoire of frames.

Data and frames are inferred through abductive reasoning. Likewise, frames are influenced by the information that is available. Seeing the data-frame relationship as reciprocal presents a number of challenges for the sensemaker, but also explains some of the complexities of interpretation and assessment of data. Data are not seen as primitives in the DF model, rather as inferred based on the current frame. Likewise, the frame is inferred from a few key anchors in the situation. The sensemaking model relies on inference as a key mechanism for understanding, however it relies on inference to the best explanation by abductive reasoning rather than the formal logics of inductive and deductive reasoning (Klein, Phillips et al., 2003; Pierce, 1903).

Data-Frame congruence stop sensemaking. One of the assertions from the model is that sensemaking will cease once the data and frame are brought into congruence; that is, the data fit the frame and the frame fit the data, without any anomalies or inconsistencies. It is not an endless effort to generate more and more inferences

Experts and novices differ by content not process. With respect to expert/novice differences in sensemaking, Klein, Phillips et al. (2007) and Sieck et al. (2007) found evidence to suggest that experts and novices reason about situations in the same way, but the experts have a richer repertoire of frames that support the sensemaking process, allowing them to perform at a higher level.

Sensemaking is pragmatic rather than rational. Sensemaking is used to achieve a functional understanding and is therefore evaluated against effectiveness in supporting action and correspondence with respect to matching external events, rather than being evaluated against abstract standards of internal consistency and coherence of formal logical reasoning. Sensemakers want to know what can be accomplished and how capabilities can be expanded, which requires the application of understanding of available resources and action capabilities.

People primarily rely on just-in-time mental models. The evidence from research by Sieck et al. (2007) suggested that the frames that people use can be external artefacts or representations as well as internal mental models that reflect causal understanding. Frames can take the form of mental models, stories, scripts, maps, and so forth; anything that provides a structure. These authors found that their use of internal representations, or mental models, was opportunistic and pragmatic with respect to their reliance on fragmentary mental models that were generated as needed, and which supported the immediate need for inference, rather than requiring complete and accurate models of the world.

Sensemaking takes different forms, each with their own dynamics. The final assertion is that sensemaking (represented by the different bubbles in Figure 3) takes several different forms, each of which has its own dynamics, and thus which might require different forms of support if we were to propose interventions or tools to improve sensemaking. The key dynamics relate to *connecting data and frame*, *questioning a frame*, *elaborating a frame*, *preserving a frame*, *re-framing*, and *constructing or finding a new frame*.

Limitations

The sensemaking model was first generated in the early 2000s based on evidence generated from several tailored research studies (Sieck et al., 2007) as well as review of past

CTA research data, which was used to identify examples of sensemaking from projects that were not necessarily designed to explore the sensemaking activities. There have been limited validations of this model since the original work, and the assertions made about how people make sense of situations largely draw on related models from other areas of psychological research (e.g., in the areas of reasoning, schema, and so forth). The model therefore represents an attempt to integrate the cognitive field research evidence with existing models of microcognition related to sensemaking into a coherent account of the macrocognitive challenges of sensemaking in complex scenarios.

Applications

The sensemaking models have been used to explore applications that support a variety of sensemaking activities including military UAV command and control (Klein et al., 2004), military signals intelligence analysis (Attfield et al., 2015; Blackford et al., 2015) and to provide general design guidance and principles for human computer interfaces (Hutton et al., 2008). In addition, the DF model has been used to provide a framework to support the development of a technique for evaluating technologies that are intended to support collaborative analysis tasks, or team sensemaking tasks (Hutton et al., 2012). The sensemaking model supports one approach to a broader set of approaches which fall under the banner of cognitive systems engineering (Hutton et al., 2003; Militello & Klein, 2013; Blackford et al., 2017) and posits an explicit approach to understanding and designing to support sensemaking challenges. In addition, the DF model has been used to develop decision skills training with an emphasis on situation assessment and understanding components of a task (Phillips et al., 2003).

A Flexecution Model of Replanning & Adaptation

The final model used to illustrate macrocognition is the flexecution model of replanning (Klein 2007a & b). The flexecution model was developed as a model of replanning and adaptation in the face of complex problems. It is derived from the term *flexible execution* where execution refers to activities conducted to achieve objectives based on some sort of plan. Complex problems are characterized by emergent and unpredictable challenges which render plans inappropriate with respect to the methods or courses of action being employed to achieve an objective, or with respect to the objectives themselves. In 1978, Klein and Weitzenfeld identified the challenges of problem solving in ill-structured problem scenarios. They identified a number of drivers and variations on how goals must change in response to emergent features of a problem situation. Subsequently, research into adaptive teams (e.g. Klein & Pierce, 2001) and in planning and replanning (e.g. Klein, 1996; Klein, Wiggins & Schmitt, 1999), identified the limitations of a *management by objectives* approach to problem solving and planning. Management by objectives assumed static, specifiable objectives at the beginning of the planning process, and implied that replanning was limited to changes in methods or courses of action in pursuit of the same goals. However, the flexecution model evolved as a solution to a *management by discovery* approach (Klein, 2011) where both courses of action and goals need to change in order to meet operational demands of obsolete, conflicting and emergent goals.

Flexecution Model

The flexecution model was derived from observations and systematic analysis of planning teams, primarily in military or emergency response domains. It was proposed as a means to describe how planners adapt to unforeseen circumstances as well as redefine goals during the operational phase of executing a plan, based on what is being learned as a plan is being executed. The need to replan and to clarify goals during an operation is rarely addressed in psychological descriptions of problem solving and planning (e.g. Hayes-Roth & Hayes-Roth, 1979). The work required to simultaneously achieve goals as well as define and redefine those goals is the focus of the flexecution model.

The flexecution model views goals as holding multiple simultaneous characteristics and serving multiple functions. Some goals are seen as foreground and providing the initial stimulus and objective for action. However other goals, including individual and organizational values which are a source of often tacit objectives remain in the background until the situation forces them into the foreground. The plan is formulated based on combinations of actions and resources to achieve the foreground goals often based on leverage points which provide additional value as the action provides a disproportionate positive influence on the outcome. However, emergent goals require the juggling of goals (between foreground and background), assessment and management of goal conflicts, and management of the inevitable trade-offs created by those conflicts.

The flexecution model recognizes that goals change as actions unfold, and that plans must be flexible with respect to their ways and means (i.e., methods and resources for achieving an objective) and their ends (i.e., the objectives themselves). Flexecution is a model of adaptive planning or re-planning, or *planning in-stride* (i.e., after a plan has been developed and communicated to those responsible for executing the plan). In a similar fashion to the processes associated with sensemaking, replanning is a continuous, closed-loop activity where the actions and objectives identified to meet the operational requirement are continuously evaluated. Inconsistencies or anomalies must be detected, validated and understood with respect to the impact on meeting the overall intent of the actions. Plans (including both methods and goals) can be adjusted and elaborated in order to improve performance. However, sometimes goals must be *reframed* in terms of the level of aspiration for success, changing priorities, adding new goal properties or deleting/refining existing goal properties, or even identifying new goals in order to achieve the higher-level intent. This is a continuous process that must be recognized and supported in order to allow decision makers to *muddle through* complex problem spaces and achieve acceptable levels of success in the face of emergent challenges which prohibit *optimization* or specification of goals at the outset. In complex environments, rigid plans with pre-specified goals and no support or leeway to adjust performance mid-stream lead to brittle plans and ultimately failure to achieve the higher-level intent and operational requirement.

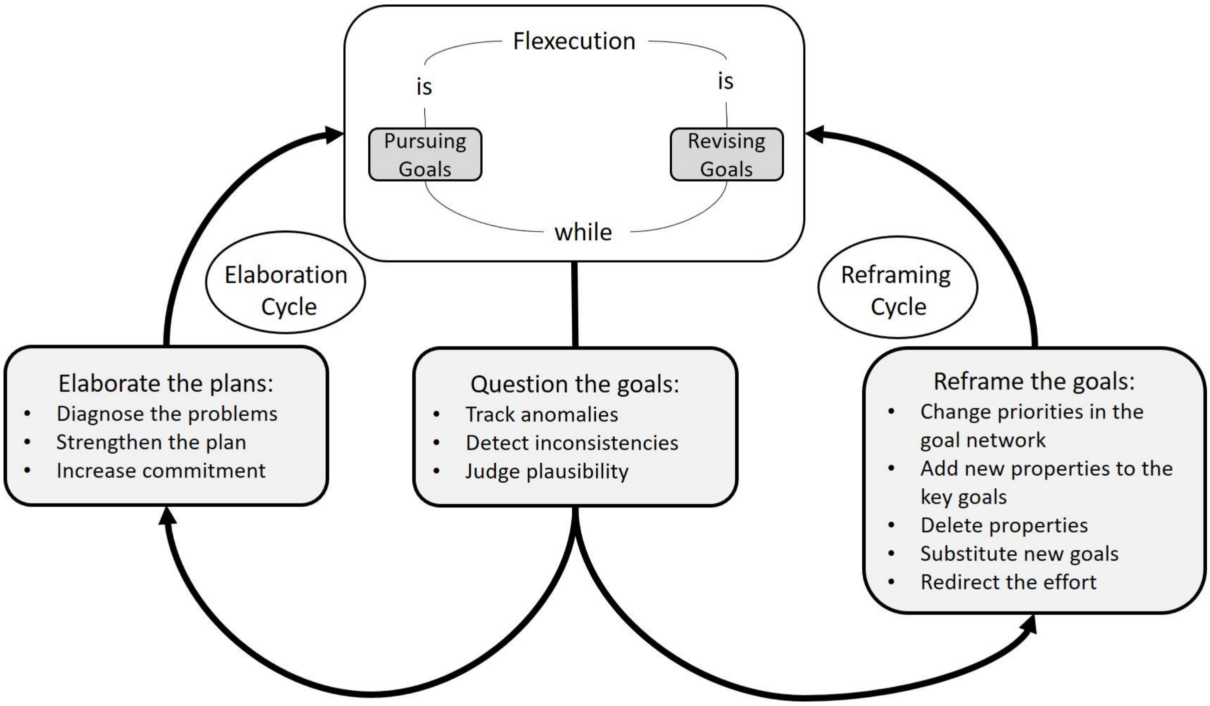

Figure 4. The flexecution process: replanning during execution (reproduced with permission from IEEE Intelligent Systems, Klein, 2007b; reproduced with permission from G. A. Klein)

With reference to Figure 4, Klein remarks of the flexecution process:

> "Because the goals are dynamic or ill defined, people need to act to learn more, taking their best understanding and pressing forward from there. Figure 1 isn't a flowchart in any traditional sense, because the macrocognitive events it depicts are largely parallel or simultaneous. Instead, it illustrates the different kinds of pathways for elaborating or reframing goals." (Klein, 2007b).

Evidence for the Flexecution Model

The evidence for this model has primarily come from a small group of researchers working primarily in military planning. The model emerged from work underscoring the challenges of wicked problems (Klein & Weitzenfeld, 1979; Rittel & Webber, 1984; Klein, 1996; Dorner, 1996; Brehmer, 2005) and field research and analysis based on exercises using observations and interviews with military planning teams (Klein & Miller, 1996; Klein et al 1996; Schmitt & Klein, 1999; Klein et al., 2000; Ross et al., 2003a & b). The pre-cursor to the flexecution model, the recognitional planning model, also fueled work by others to look at rapid replanning in complex operational environments (Thunholm, 2005; Cheah et al., 2005).

The biggest challenge to evaluating and validating aspects of the flexecution model lie in the need for decision making environments that are complex enough to generate the cognitive demands on both the planners and the operators who execute those demands. Simulation and experimental paradigms often fail to provide either the levels of complexity and drivers of adaptation, and/or the requirement to execute a plan for long enough to generate feedback on progress and the demand signals for adaptation. This has hindered the generation of empirical evidence and evaluation of models of replanning, such as the flexecution model.

Limitations

The key limitation associated with this model is its lack of external empirical validation. It is primarily a descriptive model that captures characteristics of real world operations in complex working environments. It has been used to sensitize planners to the challenges of planning and conducting operations in complex environments through education and training interventions in military command and staff colleges. In addition, there have been suggestions made with respect to implications for organizational planning processes and to the design and engineering of planning tools (e.g. Klein & Miller,1999;

Thunhom, 2005; Cheah et al., 2005). However, there are few explicit evaluations of the flexecution model or testing of hypotheses that might be generated from the model.

Applications

In terms of implications and applications in real-world settings, as described above, the flexecution model has been used for purposes of education and training in a military context. In addition, there are implications and recommendations for doctrine, processes and operating procedures which have been suggested (e.g. Hoffman & Shattuck, 2006; Thunholm, 2005; Schmitt & Klein, 1999; Ross et al., 2004). Likewise, implications for designing software tools to support planning and execution in complex operational environments, but there are no fielded examples nor rigorous evaluation studies.

Future Directions

The variety of macrocognitive models has evolved over time and continues to evolve, and mature. Early models of cognition in context were more like information processing models, however, more recent efforts have attempted to capture the continuous nature of thought and purposeful cognition in closed-loop macrocognitive models. What counts as a macrocognitive model is as much about the context in which cognition occurs as it is about what is going on inside the head (see Flach & Warren, 1995). Critically, macrocognitive models represent purposeful activity, based on experience, in context, sometimes distributed, often studied using cognitive field research methods.

Until recently, models of macrocognition have tended to develop as a series of related but not integrated models. As identified previously there are implied connections between the various macrocognitive models such as the diagnosis loop variation of the RPD model and the Data-Frame sensemaking model, as well as other examples of more elaborated subcomponents of models such as the mental simulation model (Klein & Crandall, 1995), which represents the COA evaluation loop of the RPD model. A case could be made that the

RPD model actually represents a framework from which many of the macrocognitive models might hang, given the level of inter-relatedness and complementarity.

More recently Hoffman (2013; Hoffman, & Hancock, 2017) has taken the macrocognitive modelling challenge a step further by proposing an integrated model of macrocognitive work in the context of sociotechnical system performance and particularly the issue of trust. Hoffman took the Data-Frame model of sensemaking and developed a revised version of the Flexecution model of replanning (Klein, 2007b) in order to provide an isomorphic representation of the two models before integrating them into an integrated model of macrocognitive work. Hoffman describes the marriage thus:

> "The closed loop at the top *(of the flexecution model)* is the counterpart to the topmost closed loop in the D/F model. Likewise, the other loops in the Flexecution model are counterparts to those in the D/F model. The two conceptual models are cut from the same cloth, one describing how people make sense of complex situations, and the other describing how people act on the basis of their understanding." (Hoffman, 2013, p. 24)

Figure 6 provides a representation of this integrated model of sensemaking and flexecution to describe adaptive cognitive performance.

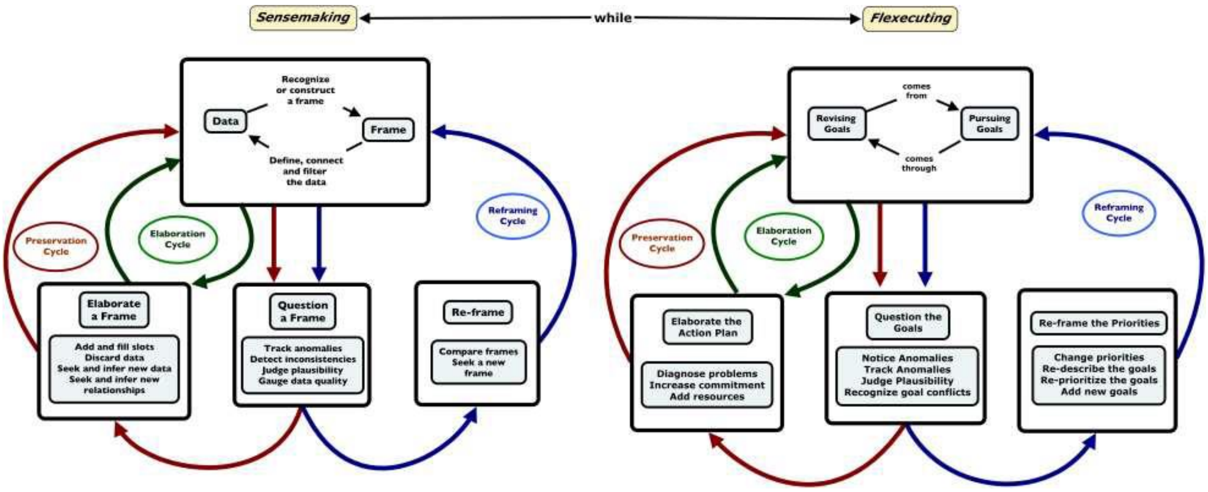

Figure 5 An integrated macrocognitive model of adaptive skill (adapted from Hoffman, 2013) - A consolidation of the Data-Frame sensemaking model and the Flexecution model (reproduced with permission from R. R. Hoffman).

Hoffman's integrated model is an attempt to reconcile two separate models originally developed in isolation. Hoffman suggested applications of this sort of modelling effort in the context of computational modelling and empirical validation of evidence for the model. He also suggested it as a means to support process tracing as a method for cognitive field research by providing potential coding themes against which to assess and understand process tracing protocols (Hoffman, 2013). Developing unifying models of macrocognition is a valuable effort to tie together the conceptual framework for understanding cognitive work, however there remains a challenge with respect to the evidence base available to validate these models, and the continued challenges of testing these models in order to generate that evidence base. Despite being in the open literature for over 10 years for example, the flexecution model has received limited feedback and challenge by the scientific community.

The diversity of models is arguably a result of the requisite variety of complex problems and applied challenges in the field, and so, it is no surprise that this has resulted in a diverse set of models. However, in researching this chapter it also became clear that there is not a recognized set of criteria for what counts as a macrocognitive model. In this chapter, I presented a one perspective in an attempt to provide a coherent story about the extant set of macrocognitive models and to provide the reader with a way to make sense of this diversity. The remaining challenge is to extend these discussions by clarifying what constitutes a macrocognitive model, determining how to develop valid and useful macrocognitive models, and specifying how they differ in meaningful ways from other models that represent complex human-machine and human-context interactions (such as models of distributed and situated cognition).

Conclusion

Understanding, describing, explaining and predicting the performance of socio-technical systems presents key challenges and increasing motivation for better models of macrocognitive work. As technologists build more and more complex machines with increasing capabilities (arguably *intelligence*), the need for us to understand how experienced people, often experts in their fields, and their technologies will interact in the accomplishment of safe, productive, and healthy work only increases. Macrocognitive models are intended to provide windows onto the *true* nature of the cognitive work that must be supported by the variety of solutions at our disposal, be they work redesign, technology solutions (including autonomous and intelligent systems), ways of working and work processes, training solutions, team and organizational design, and so forth. In addition, macrocognitive models tend to describe expert levels of performance, given that they are developed based on evidence from professionals overcoming the challenges of their work contexts. These models describe the cognitive work required to work at the edge of performance envelopes driven by the contextual drivers of adaptation namely uncertainty, time pressure, dynamic, and unexpected situation trajectories. Macrocognition as the study of cognitive adaptations to complexity (Schraagen et al., 2008) provides a powerful way for us to begin to understand expertise at the edge of these performance envelopes and to begin to develop applied solutions to these performance challenges.

Acknowledgements

The author would like to thank Robert Hoffman and Jan Maarten Schraagen for their contributions to improving the arguments, content and flow of this chapter.

References

Attfield, S., Fields, B., Wheat, A., Hutton, R. J. B., Nixon, J., Leggatt, A., & Blackford, H. (2015, June). Distributed sensemaking: a case study of military analysis (pp. 9-12). In *Proceedings of the 12th International Conference on Naturalistic Decision Making, McLean, VA, USA*

Blackford, H., Nixon, J., Malin, A., Attfield, S., Hutton, R., & Leggatt, A. (2015). *Multi-Source Information Assimilation to Support Decision Making: Final Technical Report.* DHCSTC, Yeovil: BAE Systems.

Blackford, H., Bessell, K., Hutton, R. J. B., & Harmer, S. (2017) *Reducing the Cognitive Burden of System Users via Cognitive Systems Engineering.* DHCSTC Report No. **Error! Reference source not found.**. Yeovil, UK: BAE Systems.

Brehmer, B. (2005). *The Dynamic OODA Loop: Amalgamating Boyd's OODA Loop and the cybernetic Approach to Command and Control.* Proceedings to 10th International Command and Control Research and Technology Symposium: The Future of Command and Control, June 13-16, McLean, VA. Command and Control Research Program (CCRP), Washington, D.C.

Brunswik, E. (1956). *Perception and the representative design of psychological experiments*. Los Angeles: Univ of California Press.

Cacciabue, P. C., & Hollnagel, E. (1995). Simulation of cognition: Applications, (pp. 55-73). In J-M. Hoc, P. C. Cacciabue, & E. Hollnagel (Eds.), *Expertise and Technology: Cognition and Human-Computer Cooperation*. Hillsdale, NJ: Lawrence Earlbaum.

Calderwood, R., Klein, G. A., & Crandall, B. W. (1988). Time pressure, skill, and move quality in chess. *The American Journal of Psychology*, 101(4), 481-493.

Cheah, M., Thunholm, P., Chew, L. P., Wikberg, P., Andersson, J., & Danielsson, T. (2005). *C2 Team Collaboration Experiment - A Joint Research by Sweden and Singapore on*

Teams in a CPoF environment. In Proceedings to 10th International Command and Control Research and Technology Symposium: The Future of Command and Control (pp. 13-16).

Crandall, B., Klein, G. A., & Hoffman, R. R. (2006). *Working minds: A practitioner's guide to cognitive task analysis*. Cambridge, MA; MIT Press.

Dörner, D. (1996). *The logic of failure: Why things go wrong and what we can do to make them right.* New York, New York: Metropolitan Books.

Driskell, J. E., Salas, E., & Hall, J. K. (1994). The effect of vigilant and hypervigilant decision training on performance. In *Annual Meeting of the Society of Industrial and Organizational Psychology, Nashville, TN*.

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors*, *37*(1), 32-64.

Fiore, S. M., Rosen, M. A., Smith-Jentsch, K. A., Salas, E., Letsky, M., & Warner, N. (2010). Toward an understanding of macrocognition in teams: predicting processes in complex collaborative contexts. *Human Factors, 52*(2), 203-224.

Flach, J. M., & Warren, R. (1995*).* Active psychophysics: The relation between mind and what matters. In J. Flach, J. Caird, & P. Hancock (Eds). *The ecology of man-machine systems* (pp. 189-209). Hillsdale, NJ: Lawrence Earlbaum.

Gibson, J. J. (1979/2014). *The ecological approach to visual perception.* (Classic edition). New York, NY: Psychology Press.

Hammond, K. R. (1988). *Judgement and decision making in dynamic tasks.* ARI Research Note 88-81. US Army Research Institute for the Behavioral and Social Sciences.

Hastie, R., & Dawes, R. M. (2001/2010). *Rational choice in an uncertain world: The psychology of judgment and decision making*. Thousand Oaks, CA: Sage.

Hayes-Roth, B., & Hayes-Roth, F. (1979). A cognitive model of planning. *Cognitive Science*, *3*(4), 275-310.

Hoffman, R. (2013, March). An Integrated Model of Macrocognitive Work and Trust in Automation. In *AAAI Spring Symposium: Trust and Autonomous Systems*. https://www.aaai.org/ocs/index.php/SSS/SSS13/paper/viewFile/5724/6002 (Retrieved: 24 May, 2018)

Hoffman, R. R., & Shattuck, L. G. (2006). Should we rethink how we do opords? *Military Review*, *86*(2), 100.

Hoffman, R. R., & McNeese, M. D. (2009). A history for macrocognition. *Journal of Cognitive Engineering and Decision Making*, *3*(2), 97-110.

Hoffman, R. R., & Militello, L. G. (2009). *Perspectives on cognitive task analysis: Historical origins and modern communities of practice.* Taylor & Francis, Psychology Press.

Hoffman, R. R., Norman, D. O., & Vagners, J. (2009). Complex Sociotechnical Joint Cognitive Work Systems. *IEEE Intelligent Systems*, *24*(3), 82-89.

Hoffman, R. R., & Hancock, P. A. (2017). Measuring resilience. *Human Factors*, *59(4)*, 564-581.

Hutton, R. J., Miller, T. E., & Thordsen, M. L. (2003). Decision-centered design: Leveraging cognitive task analysis in design. In E. Hollnagel (Ed.) *Handbook of cognitive task design*, (pp. 383-416). Mahwah, NJ: Lawrence Earlbaum.

Hutton, R., Klein, G., & Wiggins, S. (2008, April). Designing for sensemaking: A macrocognitive approach. In *Sensemaking Workshop, CHI* (Vol. 8). https://sites.google.com/site/dmrussell2/Hutton-sensemaking-final.pdf (Retrieved 25 May 2018).

Hutton, R., Attfield, S., Wiggins, S., McGuinness, B., & Wong, W. (2012). Team sensemaking assessment method (TSAM): An inspection method for evaluating collaborative analysis technologies. In M. Anderson (Ed.), *Contemporary ergonomics and human factors* (pp. 418-420). Boca Raton, FL: CRC Press.

Kaempf, G. L., Klein, G., Thordsen, M. L., & Wolf, S. (1996). Decision making in complex naval command-and-control environments. *Human factors, 38*(2), 220-231.

Kahneman, D. (2011). *Thinking, fast and slow*. London: Macmillan.

Kahneman, D., & Klein, G. (2009). Conditions for intuitive expertise: A failure to disagree. *American psychologist*, *64*(6), 515.

Klein, G. (1993). *Naturalistic decision making: Implications for design* (No. CSERIAC93-01). WPAFB, OH: University of Dayton Research Institute.

Klein, G. (1996). Nonlinear Aspects of Problem Solving. *Information & Systems Engineering,* Dec, Vol 2, Issue 3/4, 195-204

Klein, G. (1997). The recognition-primed decision (RPD) model: Looking back, looking forward. In C. E. Zsambok & G. A. Klein (Eds.) *Naturalistic decision making* (pp. 285-292). New York, NY: Psychology Press.

Klein, G. A (1999). *Sources of power: How people make decisions.* Cambridge, MA: MIT Press.

Klein, G. A (2004). *The power of intuition: How to use your gut fgeelings to make better decisions at work.* New York, NY: Doubleday Publishing.

Klein, G. (2007a). Flexecution as a paradigm for replanning, part 1. *IEEE Intelligent Systems*, *22*(5), 79-83.

Klein, G. (2007b). Flexecution, part 2: Understanding and supporting flexible execution. *IEEE Intelligent Systems*, *22*(6), 108-112.

Klein, G. A (2011). *Streetlights & shadows: Searching for the keys to adaptive decision making*. Cambridge, MA: MIT Press.

Klein, G. A., Calderwood, R., & Clinton-Cirocco, A. (1986, September). Rapid decision making on the fire ground. In *Proceedings of the Human Factors and Ergonomics Society annual meeting* Vol. 30, No. 6, pp. 576-580. Thousand Oaks: SAGE Publications.

Klein, G. A., Calderwood, R., & Clinton-Cirocco, A. (1988). Rapid decision making on the fire ground. Army Research Institute Technical Report 796. Aberdeen, MA: Army Research Institute.

Klein, G. A., & Weitzenfeld, J. (1978). Improvement of skills for solving ill-defined problems. *Educational Psychologist, 13*, 31–41.

Klein, G., Wolf, S., Militello, L., & Zsambok, C. (1995). Characteristics of skilled option generation in chess. *Organizational behavior and human decision processes*, *62*(1), 63-69.

Klein, G., & Crandall, B. (1995). The role of mental simulation in problem solving. In P. Hancock, J. Flach, J. Caird, & K. Vicente (Eds.), *Local applications of the ecological approach to man-machine systems* (Vol 2). Hillsdale, NJ: Lawrence Earlbaum.

Klein, G., Schmitt, J., McCloskey, M., Heaton, J., Klinger, D., & Wolf, S. (1996). *A Decision-centered Study of the Regimental Command Post.* Final Contract USC PO 681584 for the Naval Command, Control and Ocean Surveillance Center, San Diego, CA. Fairborn, OH: Klein Associates.

Klein, G., & Wolf, S. (1998). The role of leverage points in option generation. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, *28*(1), 157-160.

Klein, G., & Miller, T. E. (1999). Distributed planning teams. *International Journal of Cognitive Ergonomics, 3*(3), 203-222.

Klein, G., Wiggins, S. L., & Schmitt, J. (1999). *Cognitive aspects of replanning at Army division-level command posts.* Final Report Contract DAAH01-99-C-R060 for U.S. Army Aviation and Missile Command. Fairborn, OH: Klein Associates.

Klein, D. E., Klein, H. A., & Klein, G. (2000). *Macrocognition: Linking cognitive psychology and cognitive ergonomics.* In Proceedings of the 5th international conference on human interactions with complex systems, University of Illinois at Urbana-Champaign, Urbana-Champaign (pp. 173-177). (Retrieved from http://www.macrocognition.com/documents/K3.pdf April 20, 2017).

Klein, G. A., & Pierce, L. (2001). Adaptive teams. International Command and Control Research & Technology Symposium. http://www.dodccrp.org/events/6th_ICCRTS/Tracks/Papers/Track4/132_tr4.pdf

Klein, G., Ross, K. G., Moon, B. M., Klein, D. E., Hoffman, R. R., & Hollnagel, E. (2003). Macrocognition. *IEEE intelligent systems*, *18*(3), 81-85.

Klein, G., Long, W. G., Hutton, R. J. B., & Shafer, J. (2004). *Battlesense: An innovative sensemaking-centered design approach for combat systems* (Final report prepared under contract # N00178-04-C-3017 for Naval Surface Warfare Center, Dahlgren, VA). Fairborn, Ohio: Klein Associates.

Klein, G., Phillips, J. K., Rall, E. L., & Peluso, D. A. (2007). A data-frame theory of sensemaking. In R. R. Hoffman (Ed.), *Expertise out of context*. *Proceedings of the sixth international conference on naturalistic decision making*, (pp. 113-155). New York, NY, USA: Lawrence Erlbaum.

Klein, G., Wiggins, S., & Dominguez, C. O. (2010). Team sensemaking. *Theoretical Issues in Ergonomics Science*, *11*(4), 304-320.

Lee, J. D., & Kirlik, A. (2013). *The Oxford Handbook of Cognitive Engineering*. New York, NY: Oxford University Press.

Letsky, M., Warner, N. W., Fiore, S. M., & Smith, C. A. P. (2008). *Macrocognition in teams: Theories and methodologies.* New York, NY: CRC Press

Militello, L. G., & Klein, G. (2013). *Decision-centered design.* In J. D. Lee, & A. Kirlik. (Eds.). *The Oxford Handbook of Cognitive Engineering*, (pp. 261-271). New York, NY: Oxford University Press.

Mosier, K. L. (1991). *Expert decision-making strategies.* NASA Technical Report. Mountain View, CA: NASA Ames

Neisser, U. (1976). *Cognition and reality: Principles and implications of cognitive psychology*. New York, NY: Freeman.

Pascual, R., & Henderson, S. (1997). Evidence of naturalistic decision making in military command and control. In C. E. Zsambok & G. A. Klein (Eds.) *Naturalistic decision making* (pp. 285-292). New York, NY: Psychology Press.

Phillips, J. K., Baxter, H. C., & Harris, D. S. (2003). *Evaluating a scenario-based training approach for enhancing situation awareness skills.* Technical Report prepared for ISX Corporation under contract DASW01-C-0036. Fairborn, OH: Klein Associates.

Phillips, J. K., Klein, G., & Sieck, W. R. (2004). Expertise in judgment and decision making: A case for training intuitive decision skills. In D. J. Koehler & N. Harvey (Eds.), *Blackwell Handbook of Judgment and Decision Making* (pp. 297-315). Malden, MA: Blackwell Publishing.

Randel, J. M., Pugh, H. L., Reed, S. K., Schuler, J. W., & Wyman, B. (1996). Methods for analyzing cognitive skills for a technical task. *International Journal Human Computer Studies*, *45*, 579-597.

Rittel, H. W. J. & Webber, M. M (1984), Planning problems are wicked problems. In N. Cross (Ed). *Developments in Design Methodology* (pp. 135–144). New York: Wiley.

Ross, K. G., Klein, G., Thunholm, P., Schmitt, J. F. & Baxter, H. (2003a). *The recognitional planning model: Application for the objective force unit of action (UA).* Proceedings to 2003 CTA Symposium, Boulder, CO. Fairborn, OH: Klein Associates.

Ross, K. G., Thunholm, P., Uehara, M. A., McHugh, A., Crandall, B., Battaglia, D. A., Klein, G., & Harder, R. (2003b*). Unit of Action Battle Command: Decision-making process, staff organizations, and collaborations.* Report prepared through collaborative participation in the Advanced Decision Architectures Consortium sponsored by the U.S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-2-0009. Fairborn, OH: Klein Associates.

Ross, K. G., Klein, G. A., Thunholm, P., Schmitt, J. F., & Baxter, H. C. (2004). The recognition-primed decision model. *Military Review, 84(4)*, 6-10. Fort Leavenworth, KS: U.S. Army Combined Arms Center.

Schmitt, J., & Klein, G. (1999). *A Recognitional Planning Model*. A paper presented at the Command and Control Research and Technology Symposium. Fairborn, OH: Klein Associates. (Retrieved 25 May 2018, from http://www.dtic.mil/get-tr-doc/pdf?AD=ADA461179)

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

Schraagen, J. M., Klein, G., & Hoffman, R. R. (2008). The macrocognition framework of naturalistic decision making. In J. M. Schraagen, L. G. Militello, T. Ormerod, & R. Lipshitz (Eds.), *Naturalistic decision making and macrocognition* (pp. 3-26). Aldershot, UK: Ashgate.

Sieck, W. R., Klein, G., Peluso, D. A., Smith, J. L., & Harris-Thompson, D. (2007). *FOCUS: A model of sensemaking.* Technical Report. Fairborn, OH: Klein Associates.

Simon, H. A. (1972). Theories of bounded rationality. *Decision and Organization*, *1*(1), 161-176.

Stanovich, K E., & West, R F. (2000). "Individual difference in reasoning: implications for the rationality debate?" *Behavioral and Brain Sciences. 23*: 645–726. doi:10.1017/s0140525x00003435.

Thunholm, P. (2005). Planning under time-pressure: An attempt toward a prescriptive model of military tactical decision making. In Montgomery, H., Lipshitz, R., & Brehmer, B. (Eds.), *How professionals make decisions* (pp. 43-56). New Jersey: Lawrence Erlbaum.

Ward, P., Gore, J., Hutton, R., Conway, G., & Hoffman, R. (2018). Adaptive skill as the *conditio sine qua non* of expertise. *Journal of Applied Research in Memory and Cognition*, *7*(1), 35-50.

Warner, N., Letsky, M., & Cowen, M. (2005, September). Cognitive model of team collaboration: Macro-cognitive focus. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 49, No. 3, pp. 269-273). Sage CA: Los Angeles, CA: SAGE Publications.

Weick, K. E. (1993). The collapse of sensemaking in organizations: The Mann Gulch disaster. *Administrative Science Quarterly*, 38(4), 628-652.

Weick, K. E. (1995). *Sensemaking in organizations* (Vol. 3). Thousand Oaks, CA: Sage.

Wickens, C. D., Hollands, J. G., Banbury, S., & Parasuraman, R. (2015). *Engineering psychology & human performance*. London: Psychology Press.