Technical Report 1379

A Cognitive Skills Research Framework for Complex Operational Environments

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14. ABSTRACT
The future operating environment is expected to be increasingly complex and ambiguous, requiring Soldiers to develop and grow their cognitive proficiency and expertise across the span of their careers. This report lays a foundation for addressing the complex cognitive skills Soldiers will need to perform effectively in future operations. We used an iterative process of literature review and analysis to produce a definition of complex cognitive skill and a framework that synthesizes research and theory on the acquisition of proficiency and expertise in complex cognitive skill. The framework, called the Complex Cognitive Skills Research Framework (CCSRF), depicts learning and proficiency acquisition as an adaptation process whereby knowledge and skills become increasingly adapted to the work and work environment and increasingly integrated to form more complex cognitive skills. The framework is intended to facilitate the assessment of complex cognitive skills and the development of curricula that support career-long proficiency and expertise development. These findings are expected to help researchers and training developers create training for Soldiers who must operate proficiently in complex operational environments.

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A COGNITIVE SKILLS RESEARCH FRAMEWORK FOR COMPLEX OPERATIONAL ENVIRONMENTS

EXECUTIVE SUMMARY

Research Requirement:

The type of skills required to perform well in today's complex and information-rich work environments are different from the types required for routine, procedural work. Substantial research performed over the past few decades has helped us understand how to train the latter skill type (e.g., Berry & Dienes, 1993; Corbett & Anderson, 1994; Gagne et al., 2005); Lockhart, 2002). The present research focuses on assessing what research and theory can tell us about the former type, which we refer to as complex cognitive skill (CCS), and its acquisition. On the basis of a review of that research and theory, we developed the Complex Cognitive Skills Research Framework (CCSRF). This framework is intended to serve as a guide for researchers, decision makers, and training practitioners who are wrestling with the challenges of how to assess and develop Soldiers so they can perform with agility in increasingly complex and cognitively-demanding future operational environments, as described by the Army's multidomain operations concept (U.S. Department of the Army, 2018).

Procedure:

We conducted a literature review, peer workshop, and candidate-definition evaluation to derive a definition of CCS. The CCS definition was assessed against a number of evaluative criteria, including complex cognitive work characteristics described in the relevant literature. For the research framework's development, we extended the literature review to include research and theory about the training and assessment of cognitive skills in complex work domains. We used the literature review to inform an iterative design process through which the CCSRF was derived.

Findings:

The CCS definition and research framework describe the acquisition of complex cognitive skill by individuals and teams. Both characterize CCS acquisition as occurring through evolutionary, adaptive, and integrative learning processes. In this report, the framework is presented in terms of dimensions, objects, and the interactive interrelationships that drive those learning processes. The framework highlights a need for research that improves our understanding of the changes that occur in the cognitive elements of CCS as proficiency is acquired. An associated need is for research paradigms, methods, environments, and measures that support the evaluation of CCS training principles and methods.

Utilization and Dissemination of Findings:

The definition and research framework produced in this research are expected to help researchers and training developers develop Soldiers who must learn to operate with proficiency in complex cognitive work domains and operations. This research should help researchers develop a more focused and coherent CCS research base. In addition, it can help training

developers choose appropriate methods and resources and design effective curriculum. The framework may also serve as a visualization tool that fosters insights, reveals research questions, and summarizes the state of relevant training and research. Future research will include assessing the definition and framework for clarity, usefulness, and usability. We anticipate that as the definition and framework evolve, researchers, decision makers, and practitioners can begin actively using it to inform their efforts to support Soldier cognitive competency assessment and development, particularly for cognitive skills applied in complex operational domains. This research framework is expected to be of use to training assessment and development as the Army moves towards multi-domain operations in complex operational environments.

A COGNITIVE SKILLS RESEARCH FRAMEWORK FOR COMPLEX OPERATIONAL ENVIRONMENTS

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A Cognitive Skills Research Framework for Complex Operational Environments

Introduction

A definition and framework of cognitive skills required for complex operational environments were developed to support research on assessment and development of Soldiers' cognitive competencies for complex conditions (e.g., work roles, operational environments, and career specializations). Rapid technological advances bring with them growth in networks of information and capability, which in turn spur the near-continuous emergence of inventive ways to employ those capabilities in multi-domain operations. As these networks, capabilities, and new employment methods emerge, they will change the nature of how Soldiers must cognitively engage with them.

In particular, Soldiers are tasked to detect, synthesize, and respond to increasing amounts of information produced by an expanding variety of sources. This requires that Soldiers be able to understand and respond to new, emergent battlespace dynamics. In emerging domains, such as Cyber, Soldiers must learn how to succeed in a dynamic, interconnected, and partially invisible environment. In today's technologically advanced military, even the seemingly simple tasks of coordinating with one's team and accurately following orders can require Soldiers to process large amounts of complex information under time pressure and environmental stressors.

In cognitively challenging domains including chess, radiology, music, and sports, skill has been shown to continue to improve across many thousands of hours of dedicated experience and deliberative practice extending across years (Ericsson, 2006; Ericsson, Charness, Hoffman, & Feltovich, 2006). Similarly, developing proficiency in the cognitively challenging operations increasingly faced by Soldiers likely requires more opportunities to gain experience and practice (Ward, Gore, Hutton, Conway, & Hoffman, 2018). Developing a better understanding of cognitive skill in complex work domains and how it is acquired, may lead to changes in training methodology that reduce learning resource demands.

Developing a better understanding of the acquisition of complex cognitive skills (CCSs) may additionally reveal that methods suited to the training of non-complex skills are different from those suited to training complex skills. In particular, an initial preparatory training period combined with periodic refresher training may work well for job assignments that tend to be routine and straightforward. It is not clear that this is an effective strategy for preparing Soldiers to thrive and develop solid proficiency in a cognitively challenging work domain, i.e., in a work domain requiring CCS. In this report, we present work that provides a foundation for supporting the investigation of how to best prepare Soldiers so that they rapidly acquire proficiency and excel in work domains and career specializations that require CCS.

More specifically, this report describes a complex cognitive skill research framework (CCSRF) that summarizes the current state of theory and research about CCS acquisition. This framework and the underlying literature synthesis illuminate empirically grounded best practices and recommendations for helping Soldiers develop CCS proficiency so they may perform effectively in complex environments. A key goal of this research is to contribute to advancing the CCS research base. The CCSRF is intended to convey what is and is not known and understood about CCS acquisition. By highlighting research questions, knowledge gaps, and concepts that require further understanding, the framework can focus research agendas, personnel, and resources to ensure Soldiers' cognitive capabilities are optimized for the modern battlespace.

Defining Complex Cognitive Skills

Numerous definitions and characterizations of complex cognition, complex cognitive work, and complex tasks can be found in the research literature. However, these definitions and characterizations are typically tailored to a particular study and used to define a variable or the focus of the research. An accepted definition of CCS that can be used by the research and training communities does not currently exist.

In this research, we address this gap by deriving a useful and generalizable definition of CCS. We anticipate that the definition will benefit both the development and execution of training. The definition is intended to be a source of common ground between and among researchers and training developers. Establishing agreed upon terms of reference can lead to synergies that in turn can produce rapid advances in both what we know about complex cognitive skill acquisition and how we assess and develop it. The definition will also serve as a tool that helps researchers and training developers communicate with decision makers about the types of work that require CCS and therefore require certain types of resources and potential changes in instructional methods and techniques.

Philosophical underpinnings. The review of the relevant literature and the subsequent evaluation of definitions include philosophical ideas on the nature of knowledge and the world. As such, a brief introduction of relevant terms is warranted. Research, theory, and methodology are influenced by their authors' views on what counts as science, i.e., on what it means to understand and know things about the world. A number of different epistemological perspectives, concerning what we know and how we know it, have emerged over the centuries.

Two of these perspectives are particularly relevant to research on complex cognitive skills: positivism and phenomenology. Positivism refers to the idea that underneath our perception and experience of the world there is a single ground-truth version of the world, and that the methods of science (e.g., scientific method, hypothesis testing) can and should be used to learn about that real world. Valid scientific methods, according to the positivist position, are those that reduce the focus of a research endeavor down to its most basic elements while structuring the experimental context and controlling for extraneous influences. Phenomenology, on the other hand, finds meaning through experience. According to the phenomenological perspective, scientific method is but one interpretive technique that can be used to learn about the world as it is experienced and understood by us. It places value on research methods that do not impose artificial structure or simplify the research space, instead seeking to reveal the inherent complexity of human experience as it is lived. Positivism is a perspective focused on controlled experimentation and observation; phenomenology is a perspective focused on interpreting the meaning of experience in everyday/naturalistic contexts. These are not necessarily opposed perspectives, but can be complementary in practice.

Both epistemological perspectives have contributed to and shaped the knowledge base surrounding complex cognitive skills and their acquisition. Therefore, we wanted our definition of CCS to be inclusive of and to foster continued contributions to both perspectives. Accordingly, among the criteria used to evaluate candidate definitions was the question of whether the definition is relatable to research communities representing each perspective.

Literature Review

From a review of the literature, we extracted 34 definitions and characterizations of complex cognition, complex problem solving, complex tasks, and complex performance environments from 44 documents including military guidance documents (*n* = 8) and the academic research literature (*n* = 36). Themes, or ways of defining complexity (e.g., defined based on knowledge comprehension requirements), were identified. Definitions and characterizations were grouped by theme. The themes are reported below in Table 1 and can also be found in Appendix A.

Reviewed articles were drawn from peer-reviewed journals and conference proceedings about cognitive work in complex, challenging work domains. Articles identified for review spanned 1988 to 2018. Government documents included U.S. Army Training and Doctrine Command (TRADOC) Pamphlets, and U.S. Army Field Manuals, a U.S. Army Doctrine Reference Publication.

To identify articles for review, we searched Google Scholar for articles using phrases such as ‘complex cognitive work,’ ‘complex cognitive skill,’ ‘expert performance complex,’ “we define complexity as,” and ‘definition complex cognition.’ We also reviewed recommended and relevant articles that cited or were cited by identified articles.

Peer workshop. Six researchers not involved in the literature review volunteered to participate in a definition-development workshop. The six have backgrounds that encompass education, military training, human factors psychology, cognitive science, and computer science. They were instructed to individually review the 34 grouped definitions and characterizations of complex cognition, complex problem solving, complex tasks, and complex environments (shown in Appendix A) and to propose one or more definitions of complex cognitive skill based on their review and their relevant knowledge and experience. Participants had the options of choosing one of the existing definitions, creating an amalgamation of those definitions, or proposing an entirely new definition. The team proposed twelve candidate definitions.

The twelve candidate definitions were presented to and discussed during a peer workshop with the six volunteer researchers and two literature reviewers. Each participant ranked candidate definitions then read to the group his or her two top-choice definitions, including any proposed edits. If they were chosen by more than one researcher, top-choice definitions were listed on a whiteboard and tallied. Group discussions led to additional edits to the definitions. The workshop produced a set of four candidate CCS definitions. After the peer workshop, the team's complementary research into the acquisition of complex cognitive skills culminated in four additional definitions.

Proposed Definitions

The definitions produced by the peer workshop (Definitions 1 through 4) and that emerged during subsequent project activities (Definitions 5 through 8) are as follows:

Definition 1. A complex cognitive skill is a collection of information and techniques used to execute a complex task. This kind of task can be rendered “complex” at a number of different levels, including the amount and type of knowledge required, the number of cognitive (and non-cognitive) internal systems being employed, the interaction or integration of these knowledge components and systems, the nature and/or length of the task itself, and the factors in the environment (such as time constraints or noise) that contribute to the complexity of the task.

Definition 2. A complex, cognitive skill requires reasoning (e.g., critical thinking, problem solving, perspective taking) informed by education, experience, creativity, and intuition to support performance in an environment that is constantly changing and not fully knowable.

Definition 3. A complex, cognitive skill is performed continuously, concurrently, and iteratively as part of the C-OODA (cognitive- observe, orient, decide, act) loop. These skills include: detecting and interpreting critical cues in the environment, matching the current situation to one’s knowledge representations (schemas), orienting within and projecting from a schema, recalling and evaluating applicable courses of action, and adapting cognitive activities based on feedback.

Definition 4. A complex, cognitive skill depends on a richly interrelated base of knowledge that, together with basic perception and information processing mechanisms, adapt and integrate in response to the dynamics and difficulties of a task and performance environment with states, demands, and response combinations so numerous and unpredictable that proficiency requires years of extensive practice and experience.

Definition 5. Complex, cognitive skill is required for tasks that feature: abstraction (i.e., requiring a mental model); multiple sources of variation; interactivity; dynamism, continuity, and simultaneity; nonlinearity; conditional exceptions; ambiguity; and uncertainty.

Definition 6. A complex, cognitive skill is a skill that has adapted to factors that introduce complexity into the performance environment. Adaptations involve continuous attunement and integration, first of low-level cognitive mechanisms and then of increasingly macro-cognitive mechanisms, as experience is gained. Acquiring CCS expertise requires relatively long periods of training and/or experience.

Definition 7. Complex cognitive skill is skill acquired through adaptation to complexity.

Definition 8. Complex cognitive skill involves: participating in joint activity distributed over time and space; coordination to meet complex, dynamic demands; coping with an uncertain, event-driven environment with conflicting goals and high consequences for failure; shaping by organizational constraints; and emergent phenomena.

Common Factors. The literature review revealed a set of nine factors that appeared across many of the definitions and characterizations of complexity in cognition, cognitive skill, and cognitive work. These factors are listed in Table 1, each accompanied by an example from the reviewed literature.

Table 1
Common Factors of Complexity in Cognition, Cognitive Skill, and Cognitive Work

Common Factors	Representative Definition
Based on a rich web of integrated knowledge	Improvisation, i.e., flexible responsiveness across a wide range of situations, depends on having "an extensive network of interconnected, easily accessible schemata" (Borko & Livingston, 1989, p. 485)
Integrated, emergent cognitive processes	"We propose to use the term complex cognition as a label for…an integration of various cognitive processes needed for a smart course of action" (Schmid, Ragni, Gonzalez, & Funke, 2011, p. 212).
Adaptation to complexity	Skilled expertise requires adaptation to the dynamics of complex work or a complex work environment (Ward et al., 2018).
Difficult to learn	"Information problem solving can be characterized as a complex cognitive skill because it takes considerable time to achieve an adequate level of competence" (Brand-Gruwel, Wopereis, & Vermetten, 2005, p. 487).
Complexity exists in the task being performed	A complex task is one in which there are multiple potential ways (i.e., paths) to arrive at the desired end-state, multiple desired outcomes (i.e., end states) to be attained, conflicting interdependence among the paths to those outcomes, and uncertain or probabilistic links among paths and outcomes (Campbell, 1988).
Complexity exists in the performance environment	**"**This complex global environment involves operations among human populations, decentralized and networked threat organizations, information warfare, and true asymmetries stemming from unpredictable and unexpected use of weapons, tactics, and motivations across all of the training domains" (U.S. Department of the Army, 2017).
Contrast with what is not complex	Simple cognition, in contrast, is defined as "a term that describes isolated capacities of single psychic functions like perception, memory, and thinking without reference to other functions" (Schmid et al., 2011, p. 212).
Involves many steps or elements	"…complexity was defined in our experiment by the number (two, three, or four) of segments that composed the figures to be drawn (Albaret & Thon, 1998, p. 12).
Produces high mental workload	**"**In contrast to simple tasks, such complex tasks have many different solutions, are ecologically valid, cannot be mastered in a single session and pose a very high load on the learner's cognitive system" (van Merriënboer, Kester, & Paas, 2006, p. 343).

Definition evaluation. The research team utilized combined literature review with working group consensus (Giacina et al., 2002) to develop the following six criteria to evaluate and compare the candidate definitions:

1. Does the candidate definition specify factors identified in the literature review as contributing to cognitive skill complexity (see Table 1)?
2. Does the candidate definition use language that is consistent with both the positivist and phenomenological perspectives (to assess its potential appeal to both the experimental and naturalistic communities, respectively)?
3. Does the candidate definition treat cognitive complexity as a function of the work environment and performance requirements or as deriving from the competencies and perceptions of the performer?
4. Is the candidate definition consistent with the Army's conceptualization of complexity ("Complex is defined as an environment that is not only unknown, but unknowable and constantly changing" [U.S. Department of the Army, 2014, p. iii])?
5. Is the candidate definition consistent with the complex-systems science literature's conceptualization of complexity; that is, does it include factors of unpredictability and nonlinearity, interactivity, interdependency, emergence, and capacity to adapt to change (Cavallo & Ireland, 2014; Glouberman & Zimmerman, 2002; Heylighen, Cilliers, & Gershenson, 2007; Poli, 2013)?
6. Is the candidate definition succinct and parsimonious?

Recommended definition. Comparison of candidate definitions against the common definition themes and the criteria listed above led to the selection of candidate CCS Definition 4. Table 2 shows how each definition (listed as D1 through D8) fared against each criterion and showing that Definition 4 (D4) was judged as meeting more criteria than any other candidate definition. The assessment of the candidate definitions is described in more detail in the paragraphs that follow.

Evaluation Criterion 1 centered on factors identified in the literature review known to contribute to cognitive skill complexity (listed in Table 1). The recommended definition was the only one to specify a knowledge base, which many reviewed sources identified as a primary feature of complex cognition and skill. The selected definition includes five additional common definition factors, as well, which is more than any other candidate definition, including integrated, emergent cognitive processes, adaptation of complexity, difficult to learn, task complexity, and environmental complexity. Factors omitted from this definition are contrast with what is not complex, number of steps, and mental workload.

Criterion 2 evaluated the candidate definitions on positivist and phenomenological perspectives. The selected definition was one of just two definitions to address both of these epistemological perspectives. At its core, the definition is phenomenological, but it suggests positivism by acknowledging the roles of basic cognition and specific environmental factors, which might be experimentally manipulated or controlled.

Criterion 3 determined whether the candidate definitions conceptualized complexity based on work requirements or on performer perceptions. The selected definition conforms to this criterion, as did all but one of the other candidate definitions. This criterion reinforces the Army and complex-systems science literature criteria, both of which define complexity in terms of characteristics of the work and performance environment. To conform to this criterion, definitions could not include the factors 'number of steps' or 'mental workload.' If the definition were to include either of those factors, it would be interpretable as supporting the notion that complexity decreases as experience is gained. According to traditional views of skill acquisition (e.g., Anderson & Schunn, 2000), as experience is gained, steps compile into fewer and fewer procedures, thereby reducing cognitive workload. In contrast, the selected definition defines a skill as a complex cognitive skill based on the demands placed on the performer, not on how well any given performer handles those demands.

Table 2
Definition Criteria Crosswalk

	Criteria					
Definition	1: Relevant Factors Specified	2: Crosses Perspectives	3: Function of work not person	4: Mirrors Army	5: Mirrors Complexity Science	6: Succinct
1	4 factors	✓		✓	✓	
2	1 factor		✓	✓	✓	
3	1 factor		✓			
4	6 factors	✓	✓	✓	✓	
5	1 factor		✓	✓	✓	
6	4 factors	✓	✓			
7	1 factor		✓			✓
8	3 factors		✓	✓	✓	

Notes. Definitions are represented as D1 through D8 in Column 1. Criteria are represented in shortened form; please refer to the full definitions in subsection *Definition evaluation*.

Criterion 4 assessed the degree to which candidate definitions were consistent with the Army's conceptualization of complexity. The selected definition addresses the main factors in the Army's definition of complexity: unknown, unknowable, and constantly changing. It does so using the terms dynamics, ambiguities, and unpredictable. Only three of the eight candidate definitions did not refer to the sources of complexity included in the Army's definition.

Criterion 5 assessed the degree to which candidate definitions were consistent with the complex-systems science literature of complexity. The selected CCS definition is consistent with the way complexity is defined in this complementary literature base. The definition addresses variety, interactivity, emergence, and capacity to adapt to change. Only three of the eight candidate definitions did not refer to sources of complexity identified in the complex-systems science literature.

Criterion 6 evaluated the parsimony of each definition. The selected definition can be criticized as lacking parsimony. The simplest yet most complete of the eight candidate definitions is one that defines CCS as simply "adaptation of cognition to complexity," which derives from writings about macrocognition (e.g., Schraagen, Klein, & Hoffman, 2008; Ward et al., 2018). That definition, however, permits users to define complexity in whatever way one wishes. Consequently, we recommend a variant that draws on the prevalent characterization of complexity in the complex-systems science literature (e.g., Heylighen et al., 2007): CCS is adaptation of cognition to complexity, with complexity defined as unpredictability, nonlinearity, and ambiguity in the performance environment.

Edits were made to improve the clarity of Definition 4, resulting in to the following final version (which we view as complementary to the proposed succinct definition): A CCS is a skill that depends on a richly interrelated base of knowledge and its integration with basic cognitive processes to produce an emergent cognitive capability that adapts to complexity in work and the work environment and which continues to adapt and evolve even following extensive practice and experience. In this version of Definition 4, the definition of complexity is provided separately: Complexity is the product of nonlinear dynamics, ambiguities, and unpredictability that are themselves produced by the existence of high degrees of interactivity and variability in system states, demands, and response combinations.

The two recommended CCS definitions are consistent with a conceptualization of complexity that can be found in the complex-systems science literature. In this literature, complexity is defined in terms of characteristics such as variety and interactivity among elements; the potential for producing new, emergent phenomena; the potential for tipping points and other forms of nonlinearity; self-organization in response to shifts in the surrounding environment; and more (e.g., Heylighen et al., 2007; Paries, 2006). This treatment of complexity contrasts with candidate definitions that point to the number of task steps or items held in working memory.

According to the two CCS definitions, cognitive skills are not considered complex based on having many steps or memory elements. These factors instead contribute to a skill being complicated. Several authors have contrasted complex with complicated (e.g., Cavallo & Ireland, 2014; Glouberman & Zimmerman, 2002; Poli, 2013). An example is highlighted in the following quote:

> In a complicated context, at least one right answer exists. In a complex context, however, right answers can't be ferreted out. It's like the difference between, say, a Ferrari and the Brazilian rainforest. Ferraris are complicated machines, but an expert mechanic can take one apart and reassemble it without changing a thing. The car is static, and the whole is the sum of its parts. The rainforest, on the other hand, is in constant flux—a species becomes extinct, weather patterns change, an agricultural project reroutes a water source—and the whole is far more than the sum of its parts. This is the realm of "unknown unknowns," and it is the domain to which much of contemporary business has shifted. (Snowden & Boone, 2007, p. 72)

The recommended definitions have the potential to impact the advancement of training research and strategy. In particular, both describe complex cognitive skill acquisition as a process of adaptation versus one of accumulation (e.g., of knowledge, procedures, and routines). This embedded characterization of the skill proficiency acquisition process has significant implications for both the questions we ask about how to improve training as well as for the training curricula and tools we put into practice.

Development of the CCSRF

The definition research described above provided a general characterization of complex cognitive skill that we will next detail into dimensions, objects, interrelations, and the processes by which they change as proficiency is acquired. To develop these framework details, we conducted a second literature review in concert with iterative brainstorming, design, and feedback cycles.

Methods

To develop the CCSRF, we conducted a literature review, team brainstorming sessions, and cyclical reviews with external team members knowledgeable in Army training doctrine and practices. Two high-level objectives influenced all framework development activities. These objectives were to develop the framework to support the identification of research needs related to the acquisition and assessment of Soldiers' complex cognitive skills and to be inclusive of a range of different research perspectives and approaches; for example, positivist and phenomenological perspectives and basic, applied, experimental, and naturalistic approaches.

Literature Review. Forty documents were reviewed and summarized. Thirty-seven were peer-reviewed journal articles or conference proceedings that discussed cognitive work in complex, challenging work domains. Three were government documents, including a workshop report, the Army training and education model, and task force report on training needs in cyber operations. To identify the documents, we conducted searches using Google Scholar and search terms that included complex cognitive skill acquisition, macrocognition, complex cognitive work, cognitive readiness, complex cognitive training, complex cognitive assessment, and expert proficiency acquisition. We additionally found relevant documents by searching documents that cited and were cited by those found via the Google Scholar search.

Team members reviewed the articles and for each article wrote an overview, listed claims made by the article requiring further research and research gaps, and extracted or summarized article content characterizing complex cognitive skills and capabilities, either specific or in general, and any findings about their nature or development (this documentation can be found in Appendix B). Two members of the research team culled excerpts referring to specific elements of cognition (e.g., knowledge, skills, cognitive strategies, expert-novice differences, and competencies). Excerpts were reviewed against culling criteria by the team lead. The two team members independently coded the resulting 139 excerpts. Complex-cognition coding themes were identified by reviewing the excerpts. New themes were added to the set when no existing theme fit a particular excerpt. All excerpts were recoded once the set of themes stabilized. Multiple themes could be assigned to a given excerpt. The two researchers coded in increments of approximately 25 excerpts, and after each increment met to discuss and reconcile their codes and to make associated changes to the set of themes, i.e., codes. Coding differences they could not reconcile were discussed and reconciled during team meetings that included two additional research team members. The final set of emergent complex-cognition research themes that we used to code included: importance and richness of knowledge structures, formation and use of mental models (i.e., of knowledge structures), anticipation, pattern recognition (a form of perceptual learning), adaptation, metacognition, problem solving, decision making, attentional control, situational awareness and sensemaking, anomaly detection, communication and coordination, and critical thinking.

Team members also reviewed articles to identify research questions suggested either directly or indirectly by the authors' assumptions, findings, or discussion. The coding process was then repeated to code 133 research questions by theme. A third team member independently reviewed the questions against the resulting set of themes to identify any themes that may have been missed.

Iterative Brainstorming and Feedback. The team iteratively derived and adapted the framework designs. Early efforts involved whiteboard sketching, brainstorming, and discussing. Subsequent efforts shifted to defining and organizing framework sub-elements. Lastly, team members critiqued the framework, identified gaps and ambiguities, and suggested Army-relevant additions such as environmental stressors and a team stabilization skill.

Results

We derived a framework that summarizes research and theory about CCS and CCS acquisition. The resulting CCSRF describes CCS acquisition as a process of cognitive adaptation and specialization tailored to the specific complexities of a given task and task environment. This adaptation and specialization occurs primarily through interactions with those complexities and in response to the feedback obtained.

The derived CCSRF is described below, accompanied by a series of graphics that gradually introduce the framework elements. Framework elements are referred to as *dimensions*, *subdimensions*, *objects*, and *interrelationships*. The term dimension refers to the highest-level organizational element in the framework. Dimensions may contain lower level organizational elements, or subdimensions, or they may contain objects. The term object is used to refer to the lowest-level elements in the framework. Interrelationships refer to an ongoing interaction among two or more framework dimensions, subdimensions, or objects.

Framework dimensions. The CCSRF specifies seven interactive dimensions. These dimensions are listed in Figure 1 below.

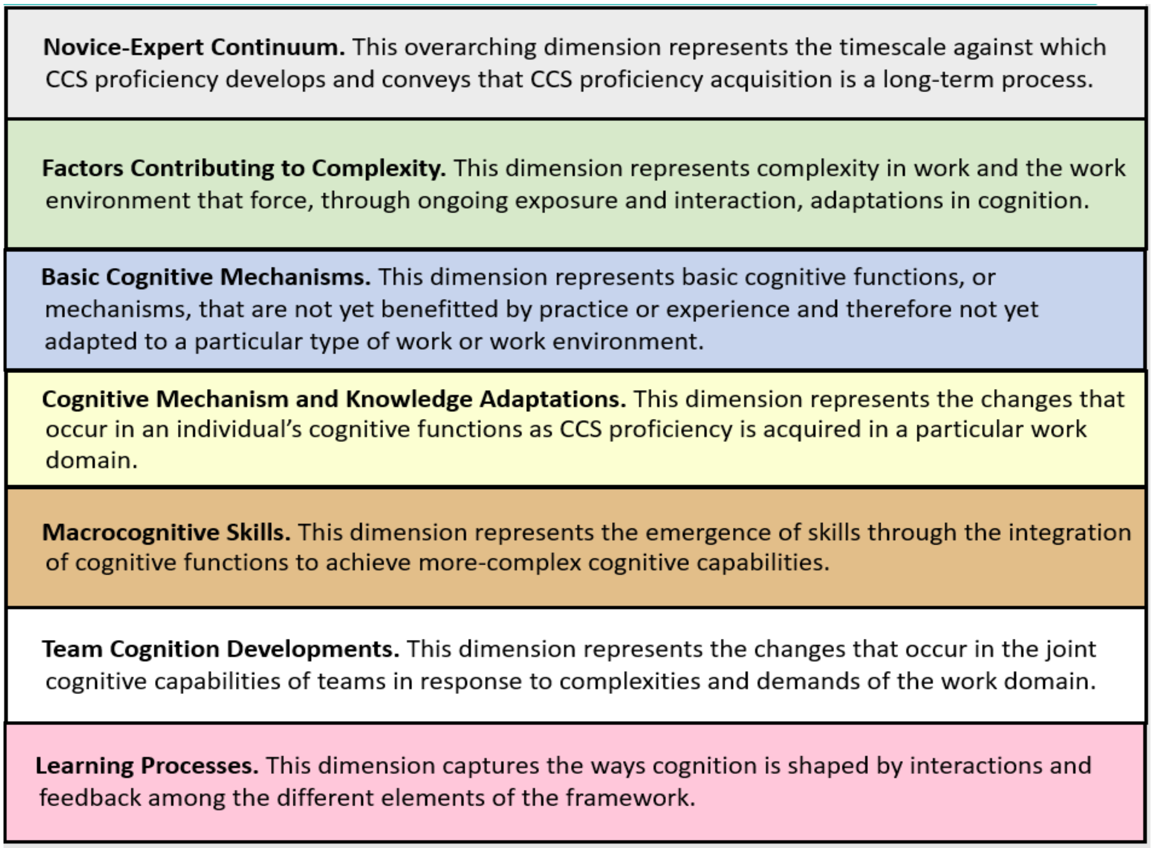

Figure 1. CCSRF dimensions.

In the sections that follow, each dimension will be detailed further, to include the identification of any subdimensions and objects within. Following dimension descriptions, we will describe the interrelationships specified by the CCSRF and how the framework elements together represent CCS acquisition. We will conclude with a discussion of research progress and needs suggested by the framework.

First, however, we present a modular view of the framework dimensions in Figure 2. This view highlights the different dimensions involved in CCS acquisition and includes details of their contents that will be discussed below. Figures 4 and 6, which we present after providing dimension descriptions, show a more complete view of the framework that includes interrelationships.

Novice-Expert continuum. The dimension shown at the very top of Figure 2 is the Novice-Expert continuum. This dimension represents the progression of cognitive skill from novice to expert as proficiency is gained. In work domains that require CCS, experts perform in markedly different ways from novices and the transition from novice to expert often extends over long periods of time and a wide variety of experiences. Table 3 summarizes eight example differences between novice and expert CCS performance as presented in two seminal papers on the subject of expertise (Dreyfus, 2004; Hoffman et al., 2014).

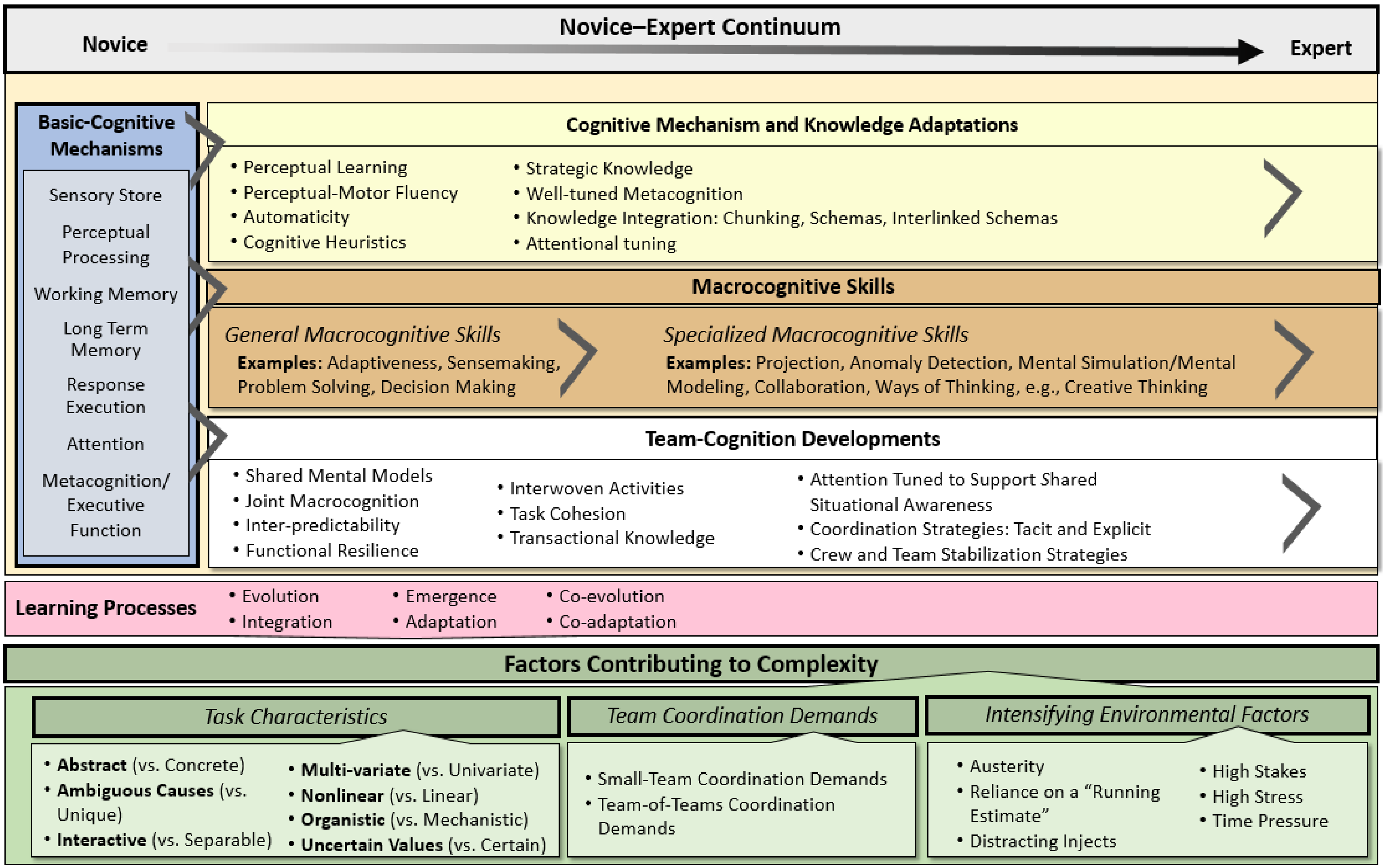

Figure 2. Depiction of CCSRF dimensions, sub-dimensions, and objects.

Table 3
CCSs and Performance Characteristics that Distinguish Experts from Novices

Example Skills	Typical Novice Characteristics	Typical Expert Characteristics
Applying learned information [1]	Not sure how to apply knowledge to specific situations (know information abstractly)	Know how to apply knowledge to specific situations
Choosing components to focus on [1]	Often chooses unimportant components based on incomplete experiences and knowledge	Experienced, know the important components
Decision-making [1]	Use analytic decision-making method (relatively slow)	Tend to make decisions using intuitive, holistic methods (fast, based on experience)
Goal orientation [2]	Seek to satisfy literal job requirements	Sets high personal standards
Reasoning[2]	Tend to make quick and wholesale judgments	Reason in skeptical and nuanced ways
Creativity [2]	Use only "by the book" methods	Can improvise and/or use non-traditional methods
Inference [2]	They infer based on memorized rules, vs attempts at causal explanation	They are more likely to consider multiple possible causes and interactions among causal forces
Metacognition [2]	Typically has not yet developed	Tend to engage in conscious, deliberate management of cognitive resources

[1] Dreyfus, 2004
[2] Hoffman et al., 2014

Basic cognitive mechanisms. This dimension, shown in the far-left panel of Figure 3, represents basic cognitive mechanisms, such as working memory and basic perceptual processes that are theorized to be the primary building blocks of cognitive skill. The CCSRF portrays basic cognitive mechanisms in a manner consistent with Atkinson and Shiffrin's (1968) information processing model. As shown in Figure 3, according to Atkinson and Shiffrin's information processing model, information flows through these basic building blocks by first entering the sensory memory store, transferring through perceptual processing to working memory stages, and then being retained in working memory via the rehearsal loop, passed on to response execution, or stored in long term memory as new or revised knowledge. Attention is the mechanism by which information is held active in these basic stores and processing mechanisms.

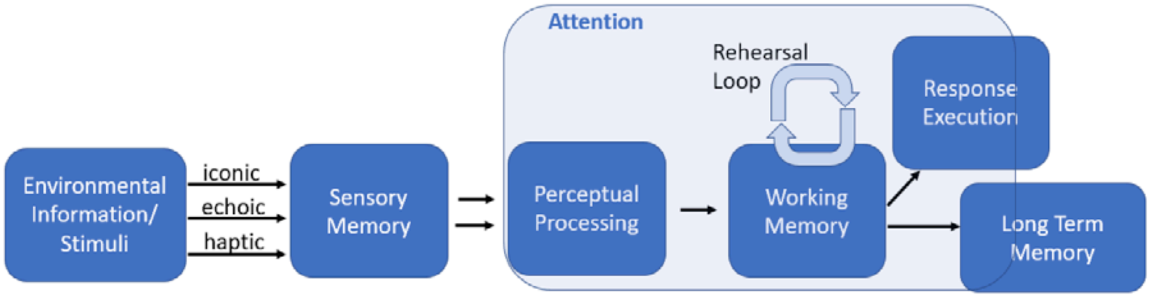

Figure 3. A variant of Atkinson and Shiffrin's (1968) Information Processing Model. *Notes.* The attention box only covers part of long term memory to indicate that only a portion of its contents are active at any given time. The attention box does not cover all of response execution to account for the theoretically attention-free execution of automatized procedures.

The seven, basic cognitive mechanisms that compose this dimension are sensory store, perceptual processing, working memory, long-term memory, response execution, attention, and metacognition. Sensory memory is where the raw perceptual information is held very briefly in the sensory store. Perceptual processing is the stage where perceived details are integrated and given meaning. For example, in Sensor Memory a tree is perceived only as textures, colors, lines, and angles. In Perceptual Processing, these attributes are integrated and recognized as objects, i.e., as leaves, branches, a trunk, and the tree itself. Working memory is where that integrated perceptual information, along with information retrieved from long-term memory, is held during active processing. Processing in working memory both tightens the connections among related information and creates more pathways for accessing and retrieving information from long-term memory. Long-term memory is where information is stored more or less permanently as knowledge and memories. Response execution is the initiation and performance of intentional actions selected in working memory. Attention is the state that exists when information is intentionally processed with awareness, it is being given attention. Metacognition, also referred to as executive function, is the capability to monitor and manage one's own cognitive activity.

As basic cognitive mechanisms are used to perform effectively within a new set of task demands and new task environment, they begin to adapt to those demands and environment (Araújo & Davis, 2011; Araújo, Davids, Chow, & Passos, 2009; Davids, Araújo, Vilar, Renshaw, & Pinder, 2013). Through this adaptation process, the basic cognitive mechanisms become attuned to the task and environment and begin to integrate and synergize to produce more sophisticated cognitive mechanisms. The process of attuning and integrating of cognitive mechanisms is a stage of proficiency acquisition that is represented in the CCSRF by the dimensions cognitive mechanisms and knowledge adaptation, macrocognitive skills, and team-cognition developments. These dimensions represent ways that basic cognition adapts in response to complexity in the task environment. They are represented by three long boxes stacked along the right side of the Basic-Cognitive Mechanisms box in Figure 2 and are described in more detail in the paragraphs that follow.

Cognitive mechanisms and knowledge adaptations. This dimension represents basic cognition as it responds and adapts to demands, pressures, and complexities of a given work domain. Objects in this dimension are, accordingly, adapted versions of basic cognitive mechanisms. The framework specifies two proposed varieties of objects in this dimension: adapted basic mechanisms and derived mechanisms.

Adapted basic mechanisms include perceptual learning, perceptual-motor fluency, automaticity, well-tuned metacognition, and attentional tuning. Perceptual learning is the accumulation of tacit knowledge and neural tuning to allow experienced performers to recognize and focus on the patterns and cues that matter, notice subtle distinctions that matter, and recognize when something is missing or changed (Gibson, 2000). We define perceptual-motor fluency as the quick and smooth initiation, calibration, control, and execution of motor responses in a way that is tightly aligned with what is being perceived. Automaticity is fast information processing not limited by use of attention and requiring little subjective effort (Shiffrin & Schneider, 1977); CCSs do not become automatic but benefit from the freeing of cognitive resources when other skills become automatized. Well-tuned metacognition refers to awareness and monitoring of one's thoughts and task performance (Flavell, 1979); with experience, it adapts to the specificities of performance requirements and demands in a given work domain. Attentional tuning occurs after developing expertise in a given domain where the performer's attention adapts to what matters, what does not matter, what to expect next, and what is high versus low priority (Vecera, Cosman, Vatterott, & Roper, 2014).

Examples of derived mechanisms include cognitive heuristics (i.e., mental shortcuts), organizational knowledge structures (e.g., chunks, schemas, and interlinked schemas), and strategic knowledge. Cognitive heuristics are mental shortcuts utilized when assessing a situation or making a decision, in order to compensate for task and environmental demands (Gigerenzer, 2008). Organizational knowledge structures are conceptual elements (e.g., templates and frames) that bind together a large amount of related information (Gobet & Clarkson, 2004; Guida, Gobet, Tardieu, & Nicolas, 2012). Strategic knowledge is knowledge about how to perform adaptively in response to challenges, including when it is appropriate to utilize cognitive heuristics, what difficulties could be anticipated, and how they can be avoided (Leithwood & Steinbach, 1995). These derived mechanisms of cognition develop as basic cognitive mechanisms that adapt and emerge in response to complexity.

Macrocognitive skills. As cognitive mechanisms adapt to complexity in task, team, and environmental demands, they become functionally integrated to support the specific types of complex cognitive work required (Klein et al., 2003). In other words, they form *macrocognitive* skills. Macrocognitive skills are defined in the research literature in a holistic way because the complexity of their cognitive elements and relationships eludes reduction into clear specific elements. Objects in the macrocognitive skills dimension are grouped into two sub-dimensions: general macrocognitive skills and specialized macrocognitive skills.

General macrocognitive skills are skills that emerge and begin to adapt to work domain complexities very early in the learning process. Examples of general macrocognitive skills include adaptiveness, problem solving, sensemaking, and decision making. Adaptiveness is characterized by knowing which strategies are appropriate for each given situation (even rare situations), attunement to cues that signal whether a strategy should be used and whether it is working, the desire to change along with the environment, and the ability to mentally organize information in multiple ways (Ward et al., 2018). Problem solving is the process of finding solutions to a given issue, which can include component processes such as defining the problem, generating candidate solutions, implementing and selecting solutions, and verifying solutions. Sensemaking is the continuous process of evaluating and connecting relevant incoming information to one's own mental models and previous knowledge (Weick, 1995). Decision making is the process of selecting a response or course of action. The basic cognitive mechanisms involved can be brought together to execute these skills from early on; however, significant adaptation and integration are required to execute them well.

Specialized macrocognitive skills are skills that emerge only after a basic foundation of knowledge and skill has formed. Examples of specialized macrocognitive skills include anticipation, collaboration, anomaly detection, and mental simulation. Descriptions related to four specialized macrocognitive skills are listed in Table 4. Note that macrocognitive skills are often described in terms of how experts manifested them.

Table 4
Specialized Expert Macrocognitive Skills

Specialized Macrocognitive Skills	Experts…
Anticipation	… use top-down processing (goals, experience, expectations) to allocate attention to events/stimuli that are most likely to be relevant to them (Klein, Snowden, & Pin, 2011)
Collaboration	… cooperate (agree on goals that are difficult to attain in transactive relationships) and coordinate (align actions to achieve those goals) with partners to accomplish what they cannot accomplish alone (Gulati, Wohlgezogen, & Zhelyazkov, 2012)
Anomaly detection	… possess relevant baseline mental models so that environmental indications can be compared against them to decipher rare events and unusual bursts of events (Branlat, Morison, & Woods, 2011)
Mental simulation	… use their mental models of reality to simulate and evaluate potential actions, which ultimately can lead to the selection of an action (Klein et al., 2003)

Specialized macrocognitive skills also include specialized ways of thinking. Proficient and expert-level performers develop ways of thinking about their work that influence how they employ metacognition, i.e., the ways they monitor and manage their own cognitive work. In the development of the CCSRF, we identified four ways of thinking that can advance hand-in-hand with proficiency: systems thinking, critical thinking, creative thinking, and skeptical stance. Systems thinking is characterized by paying attention to and being mindful about the larger system in which any given element or action has influence or plays a role. Critical thinking is a reflective state characterized by reasoned thinking focused on deciding what to believe or how to act. Creative thinking generates nonobvious or unusual interpretations, future states, actions, uses for objects, or connections, and is often accompanied by openness to new ideas. Skeptical stance is a state characterized by remaining open to and vigilant for incoming data that call into question or conflict with one's assessment of a situation.

Interrelationships and learning processes. The critical role of interactions and feedback within the framework means that interrelationships are also critical to learning (see Figure 4). Interrelationships between complexity in the work domain and cognitive elements of the framework are, therefore, central to the adaptation of cognition and to CCS proficiency acquisition. Interrelationships among cognitive elements and the associated interactivity are also necessary for another critical aspect of CCS proficiency acquisition: they allow cognitive elements to integrate in synergistic ways and co-optimize to achieve advanced and sophisticated levels of cognitive capability in a given work domain.

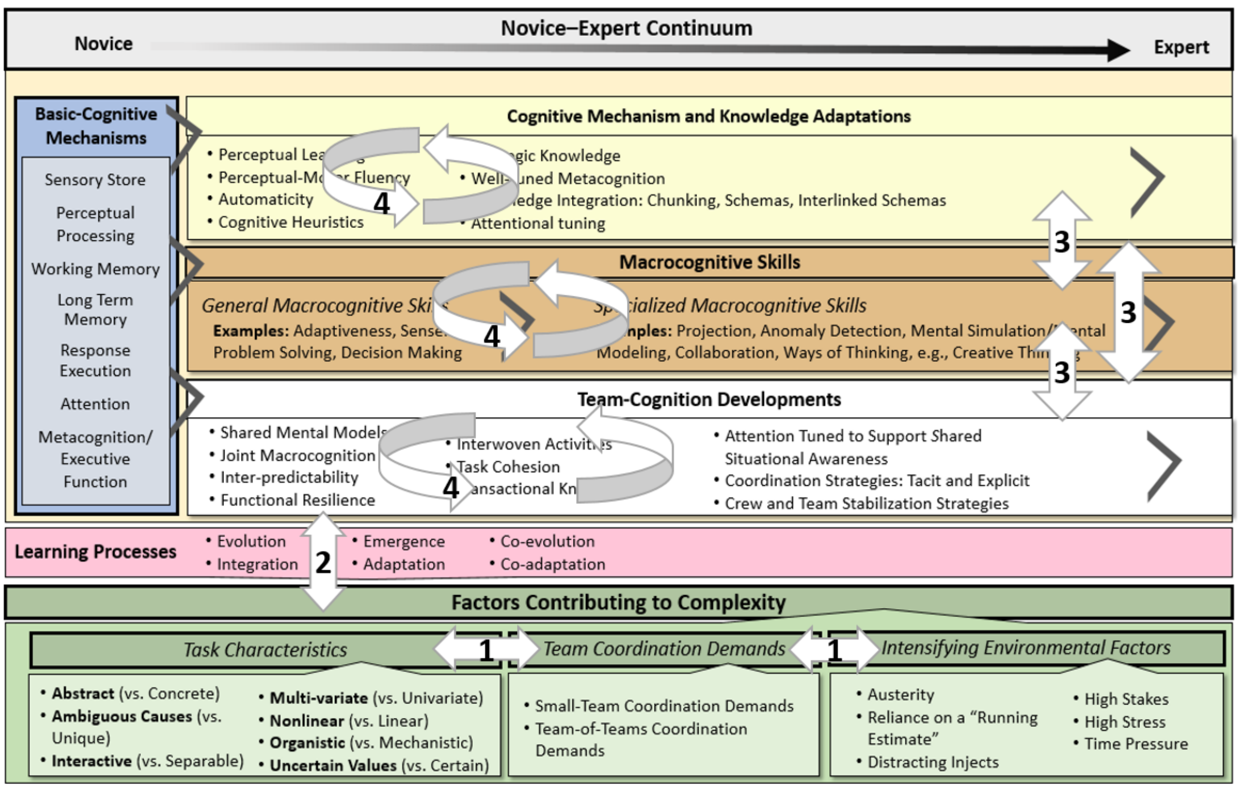

Figure 4. CCSRF interrelationships that produce learning processes. *Note*. White numbered arrows correspond to interrelationships in the numbered list below.

All elements (i.e., dimensions, sub-dimensions, and objects) of the CCSRF have the potential to interact and thereby shape and be shaped by other elements of the framework. Interrelationships that most influence CCS proficiency acquisition are listed below and numbered for the purpose of referencing them in Figure 4.

1. Factors Contributing to Complexity interact with other Factors Contributing to Complexity to increase work domain complexity. Work domain complexity is a function of the confluence of all the complexity factors characterizing that

domain. These factors interact to increase unpredictability, i.e., complexity, within the domain.

2. Factors Contributing to Complexity interact with all cognitive elements of the framework, i.e., with Basic Cognitive Mechanisms, Cognitive Mechanism and Knowledge Adaptations, Macrocognitive Skills, and Team-Cognition Developments.
3. The cognitive elements of the framework interact with one another, e.g., Cognitive Mechanism and Knowledge Adaptations interacts with Team-Cognition Developments.
4. The objects within the framework's cognitive elements, i.e., specific Cognitive Mechanism and Knowledge Adaptations, Macrocognitive Skills, and Team-Cognition Developments, interact with each other to produce and advance integrative, synergistic cognitive capability.

Factors contributing to complexity. The dimension called factors contributing to complexity is shown at the base of Figures 1 and 3. In the CCSRF, complexity in a work domain exists when there is unpredictability, nonlinearity, and ambiguity in the performance environment (e.g., Heylighen et al., 2007). This dimension plays a critical role in the framework. It represents the pressures that necessitate cognitive adaptation and development in complex ways, producing CCS. Factors, or objects, that contribute to complexity are classified within the framework as sub-dimensions, and include task characteristics, team coordination demands, and environmental factors. Task characteristics, such as nonlinearity and ambiguous cases, are described in detail in Table 5. Team coordination demands correspond with teamwork factors such as small-team coordination demands and team-of-teams coordination demands. Environmental factors can have an intensifying effect on complexity. Examples of environmental factors include (a) high stakes— the potential for significant gains or losses (e.g., human life, resources); (b) austerity—a lack of normal amenities and resources, such that coping depends on resourcefulness and determination; (c) distracting injects— unexpected events that add to the complexity of an existing problem or challenging situation; (d) high stress—a state experienced when environmental demands tax one's resources or endanger one's well-being; (e) time pressure—a condition experienced when time to respond or accomplish a goal is limited; and (f) reliance on a running estimate—the situation assessment and projection depend on dynamic assumptions, versus on known facts.

Learning processes. The Learning Processes dimension, depicted by the loops in Figure 5, defines the types of learning processes produced by the interrelationships within the CCSRF. The six learning processes are adaptation, co-adaptation, emergence, integration, evolution, and co-evolution. Adaptation is a process whereby entities, processes, systems, and environments change in response to the influence of other entities, processes, systems, and environments with which they regularly interact. Co-adaptation is the process of adaptation when it is mutual, occurring in parallel in two or more entities, processes, systems, or environments within the same system as they interact and influence one another. Emergence is the process through which the interactions among elements (e.g., variables, entities, systems, etc.) produce a new element, process, capability, phenomenon, or state that is different from the contributing elements and cannot be reduced down to those elements or their individual effects. Integration is the process of interweaving, combining, or adding of elements, processes, systems, or capabilities to produce a new, more complex element, process, system, or capability. Evolution is the change produced by the survival and selection of characteristics, capabilities, entities, and processes based on their robustness to selective pressures and contribution to the health and robustness of the system in which they exist. Co-evolution is a process by which one characteristic, capability, entity, or process changes in response to pressures caused by another characteristic, capability, entity, or process that, in turn, is changed by pressures produced by the other. For example, individual and team cognition are depicted in the CCSRF as interacting and co-evolving. Team-cognition capabilities influence and shape individual cognitive capabilities and vice versa.

Table 5
Task Characteristics that Contribute to Task Complexity

Task Characteristic	Description
Abstract (vs. Concrete)[1]	Difficult to physically observe; cause/effect not easily observed
Ambiguous Causes (vs. Unique) [2]	A given combination of circumstances can result in any of multiple outcomes or given outcome can be result of many combinations of circumstances, making it impossible to know exactly what circumstances led to what outcome
Interactive (vs. Separable) [1]	Underlying causes interact, so the effect of one variable might change depending on status of another variable
Multi-variate (vs. Univariate)[2]	Multiple variables contribute to any given outcome
Nonlinear (vs. Linear) [1]	Relationship between underlying dimensions and outcome could be exponential, logarithmic, etc.
Organistic (vs. Mechanistic) [1]	The effects are the product of more holistic, organistic functions
Uncertain Values (vs. Certain) [2]	Variable values might have to be estimated or extrapolated/interpolated

[1] Feltovich, Coulson, & Spiro, 2001
[2] Wulfeck, Wetzel-Smith, & Dickieson, 2003

The framework's interrelationships are the glue that tie together its dimensions, sub-dimensions, and objects and that force them to progress toward higher levels of proficiency. In Figure 5, we present the individual-level CCSRF representation in order to call attention to the main framework interrelationships and the ways they contribute to CCS acquisition.

Figure 5 portrays CCS acquisition as a process whereby basic cognitive mechanisms, once exposed to complexity of a given work domain, begin to adapt to that complexity. As the adapting mechanisms continue to interact with that complexity (interactivity is represented by loops), they continue to adapt, integrate, and evolve, i.e., learn and gain proficiency or even expertise in that domain. The figure shows a central column of horizontal arrows that represent progression in specific individual cognitive mechanism and knowledge adaptations. These arrows initiate in basic cognitive mechanisms and extend across the entire learning process, which may encompass a period of many years.

Of note is the arrow labeled Knowledge Integration. Our literature review emphasized the central role in CCS of rich, extensive, and highly interlinked domain-specific knowledge. Thus, although the knowledge integration arrow resembles the other horizontal yellow arrows, it is central and essential to learning and proficiency growth in the cognitive mechanisms represented by the other arrows.

The horizontal arrows encompass a macrocognitive skills dimensions in addition to cognitive mechanism and knowledge adaptations. Macrocognitive skills are represented as a single large horizontal arrow among many narrower arrows. This arrow encompasses the full set of smaller arrows to connote the integration of the many arrows into macrocognitive skills.

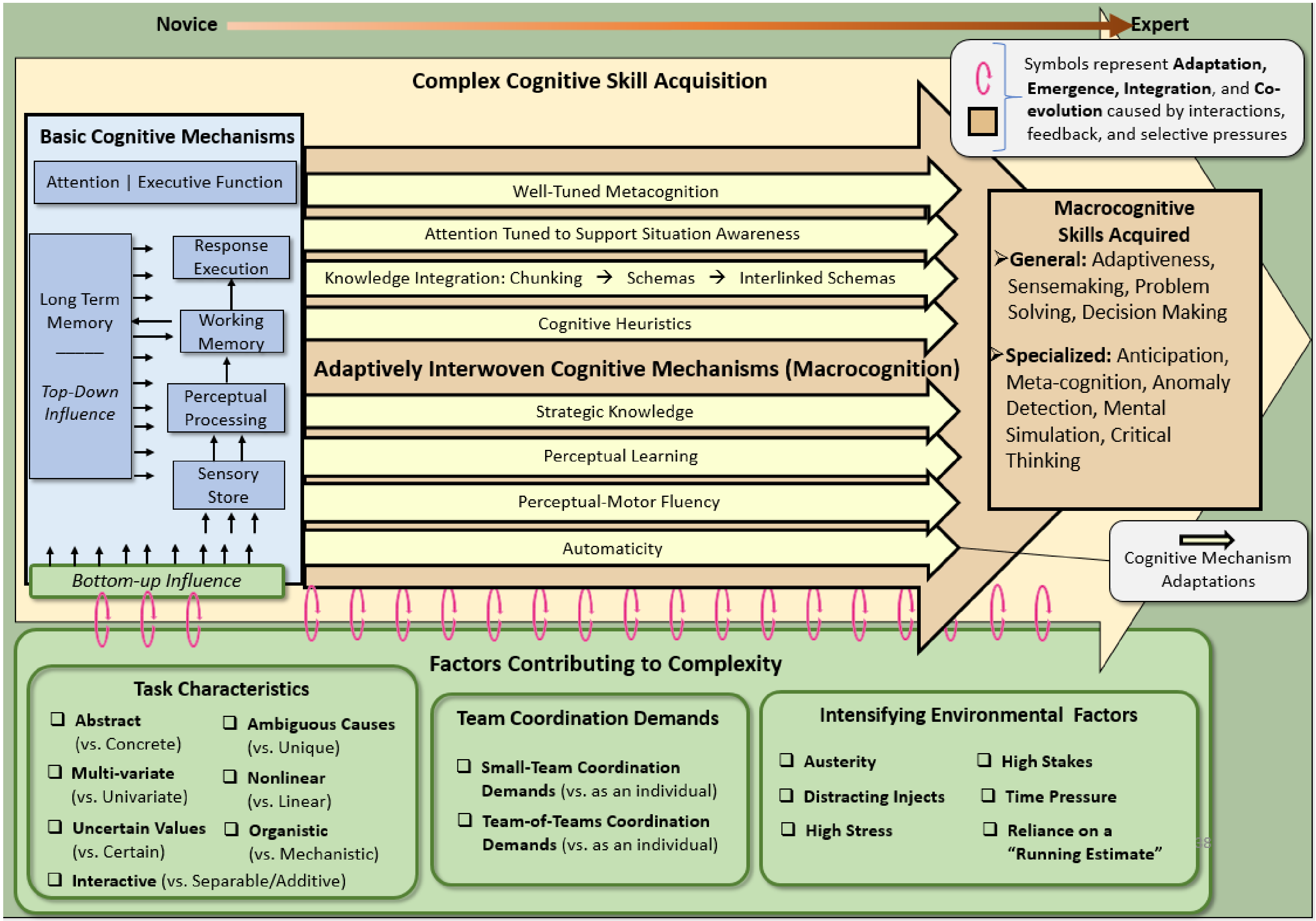

Figure 5. CCS elements progression from a novice to expert proficiency.

Team-cognition developments. Teams can acquire and perform CCSs just as individuals can. The path to proficient CCS performance by a team (or "team of teams") requires adaptations to the ways cognitive work is jointly performed; for example, how knowledge is shared, situations are assessed, and performance is monitored (Cuevas, Fiore, Caldwell, & Strater, 2007; Fiore, Ross, & Jentsch, 2012; Salas & Fiore, 2004). Team CCS acquisition is a process that accompanies individual-level cognitive mechanism adaptations. Many team-level cognitive adaptations may be viewed as direct counterparts to cognitive mechanism and knowledge adaptations. For example, in the CCSRF, knowledge integration at the individual level takes the form of shared mental models and transactive memory at the team level. Attentional tuning at the individual level takes the form of attention tuned to support shared situational awareness at the team level. Because multiple cognitive mechanisms come together with one another and with relevant knowledge structures to produce team-cognition capabilities, these capabilities can be considered a form of macrocognition. In Table 6, we present a number of example team-level CCSs.

Figure 6 presents a view of the CCSRF that highlights team-level learning processes and CCS acquisition. The growth and adaptation of team cognition in response to domain complexity is depicted by the top horizontal arrow. Growth and adaptation in team-level CCSs accompany cognitive mechanism adaptations at the individual level (i.e., as shown in Figure 4). Loops connecting the team- and individual-level arrows represent interactions between individuals and their teams, which produce emergence and co-evolution in both individual and Team CCS. Although all team-level cognition can be considered macrocognitive, the CCSRF depiction in Figure 6 includes a box that specifies joint macrocognitive skills for the purpose of mirroring and contrasting with individual-level macrocognitive skills presented in Figure 4's individual-level framework representation.

Table 6
Examples of Team-Level CCSs

Team-level CCS	Description
Task cohesion	The degree to which members of a team cooperate to achieve common performance goals (Jowett & Chaundy, 2004).
Shared mental models	Knowledge structures that members of a team have in common that allow them to respond to task demands and one another in coordinate and anticipated ways (e.g., Jonker, van Riemsdijk, & Vermeulen, 2011); similar to the concept of common ground.
Attention tuned to support shared situation awareness	With experience in a given domain, the team learns to, either as a united whole or by distributing responsibility among individual members, understand and pay attention to what matters, know and look for what to expect next, and understand and adjust attention to high versus low priority information and work.
Tacit and explicit coordination	Tacit coordination: Team members choose which activities to perform based on knowledge of other team members' expertise and behavior patterns (e.g., Wittenbaum, Stasser, & Merry, 1996). Explicit coordination: Outward plans are made between team members to align actions to agreed-upon goals (e.g., Gulati, et al., 2012).
Transactive memory/knowledge	A collective approach to information and knowledge management whereby different team members take responsibility or, over time, become responsible for remembering and recalling certain types of information on behalf of the team (Wegner, 1987).
Joint sensemaking	The process of connecting pieces of environmental information in a way that is mutually agreed upon by team members (Weick, 1995).
Inter-predictability	The ability of a team member to foresee and adapt to how another team member will react to a given development.
Interwoven activities	Team member activities that have co-evolved such that they are performed in complementary, integrated ways in support of team goals.
Functional resilience	Ensuring that a team is resilient by assigning multiple team members to pursue similar goals or perform similar functions.
Crew and team stabilization	Maintaining team effectiveness despite perturbations such as loss of a team member or the addition of new members.

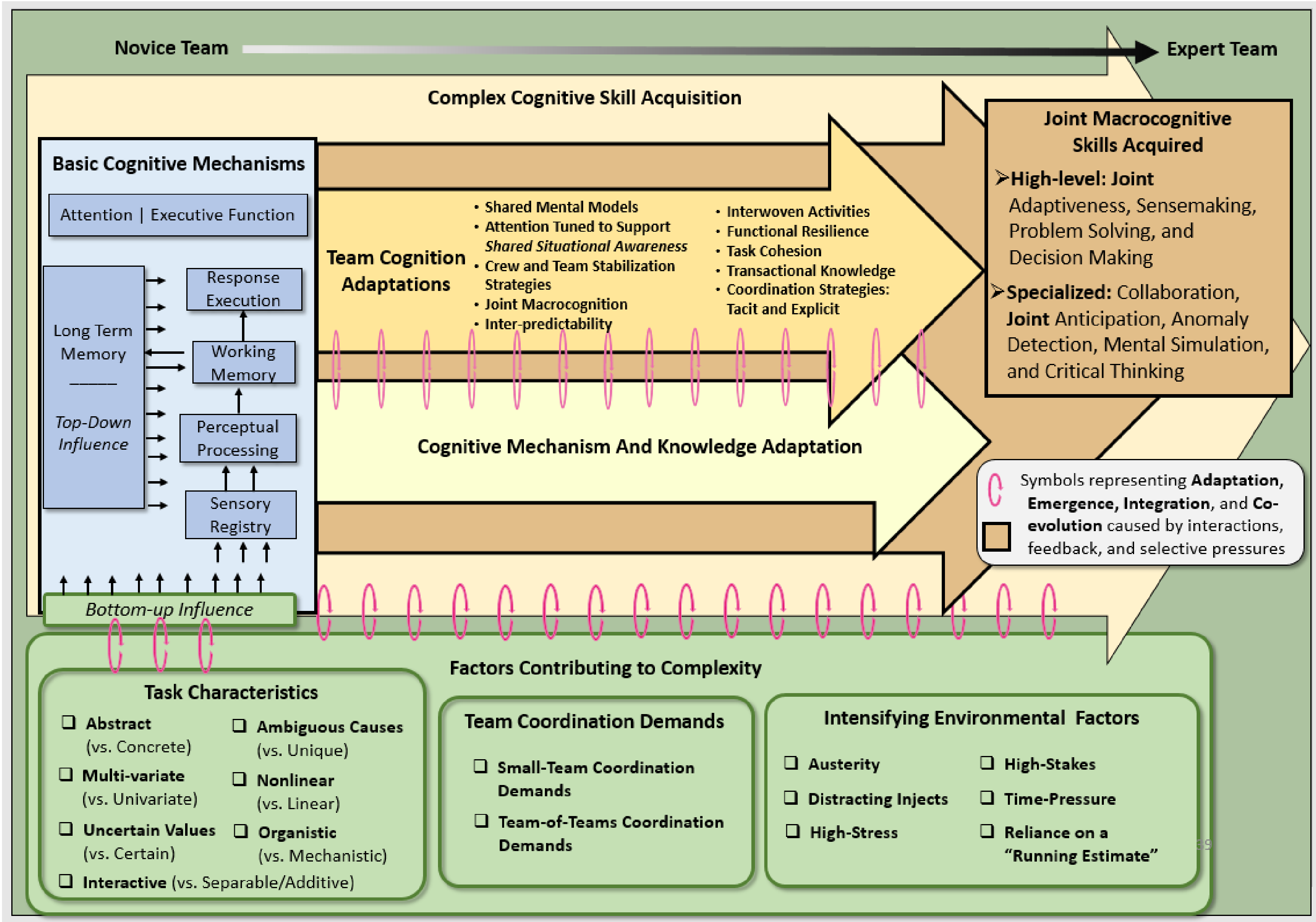

Figure 6. Depiction of CCSRF that highlights acquisition of CCS proficiency by teams.

Discussion

We have proposed a framework that summarizes CCS research. The CCSRF represents CCSs in terms of their relationship with basic cognitive mechanisms, complexity in a given work environment, and interrelationships that produce learning via cognitive adaptation and evolution. CCSs are represented as multidimensional and emergent products that come in holistic, macrocognitive forms (e.g., sensemaking); microcognitive forms (e.g., perceptual fluency); and team-cognition forms (e.g., collective sensemaking).

The CCSRF portrays CCS learning and proficiency acquisition as occurring through processes of adaptation, evolution, emergence, and integration. This perspective of learning has significant implications for how training is conducted. First, it implies that initial learning conditions should be designed to lay groundwork for a flexible, continuously growing, and adaptive knowledge base. Initial learning conditions should be designed so that learners develop adaptations that scale to the complex environment in which they ultimately must perform. Second, across their careers, practitioners' experiences and assessments should encourage and guide continued adaptation that is responsive to work-domain changes to a diverse range of domain challenges and conditions and to increasingly sophisticated and detailed domain features and regularities. To capture the adaptive character of learning, skill assessment should be sensitive to changes in knowledge, macrocognitive skill, and the attunement and refinement of cognitive mechanisms such that improvements can be detected as practitioners transition from novice to journeyman, from entry-level journeyman to advanced journeyman, from advanced journeyman to expert, and possibly from expert to master across an extended, years-long proficiency and expertise acquisition process.

The adaptation perspective of learning similarly impacts the research questions we choose to pursue. The adaptation-perspective-based training goals outlined in the paragraph above each require attention from the research community. Specifically, research is needed on initial learning conditions and on figuring out how best to support experienced personnel in becoming as proficient as possible. To effectively pursue these and other relevant research lines, research is needed to develop research paradigms and sensitive measures of CCS proficiency.

Challenges to the Study of CCS Acquisition

Studying the acquisition of skill in complex cognition is a challenging endeavor. Research opportunities and resources are needed that support longitudinal studies. In addition, research strategies, methods, and measures need to support research in complex work environments.

As an example, simulations such as the Army's Virtual Battlespace environment can be designed to offer a complex cognitive domain in which to conduct research. Furthermore, simulations may be used to collect the large sample size required in research in which control is limited. However, simulation systems are rarely instrumented to support the collection of the process or diagnostic measures needed to assess cognitive skill. Inadequate instrumentation of the complex environments in which CCS can be studied is a common obstacle. Exceptions exist (e.g., Cooke & Shope, 2004) but are few in number, and this has impeded the development of a productive CCS research community. A related obstacle to CCS research is time. CCS proficiency has been shown to progress across a time scale of many years (e.g., Ericsson, 2006), a time scale that most study participants cannot support.

Although experimental research conducted in a laboratory is not well suited to the study of complex cognitive work, it is widely considered the proper means for advancing science. In contrast, research conducted in complex environments is less likely to produce the kinds of statistically significant outcomes that impress the scientific community. In these environments, experimental control is inherently limited. The variability and interactions that produce complexity conspire against controlled comparisons of well-defined conditions. While portions of the research community recognize the value and power of naturalistic and qualitative research methods for advancing our understanding of complex cognitive work and the underlying science, the positivist perspective remains a dominant influence.

We recommend research methods, education, and funding resources that support the advancement of naturalistic and qualitative research methods aimed at improving CCS training interventions and their assessments over extended periods of time. Investment in new and enhanced research environments for studying complex cognitive work, both experimentally and using more naturalistic methods, is also recommended. More researchers, research organizations, and research sponsors might contribute to the identified research needs if the scientific community developed and advocated a greater variety and number of scientific methods for approaching complex problems and studying them in ways that preserve their complexity.

Accomplishments in the Study of CCS

Significant research is required in order to fill in knowledge gaps highlighted by the CCSRF, especially to better understand how different elements of the framework evolve and integrate and how to optimize and assess their development. For example, one potential gap is the lack of integration of non-cognitive aspects within CCS. The CCS framework enumerates factors contributing to complexity (e.g., task characteristics, team demands, and environmental factors), but does not yet address interaction between cognitive and non-cognitive skills. On the positive side, sufficient research and theory exist to support the derivation of a high-level representation of CCS and its acquisition. Researchers have, over decades of research on expertise acquisition, produced robust characterizations of experts and expertise (e.g., Ward, Schraagen, Gore, & Roth, in press). Based on this research base, we have a comprehensive understanding of the cognitive capabilities and resources needed for performing CCS.

Researchers have proposed a number of training guidelines and strategies for developing CCS acquisition. For example, Ward et al. (2018) have proposed the following set of principles for supporting expertise acquisition in complex cognitive work:

- Principle 1: Flexibility-Focused Feedback – teach learners when their current strategies work effectively and when they will not; promote the development of new strategies and conceptions; and help them quickly re-assess and reassemble current knowledge.

- Principle 2: Concept-Case Coupling – provide opportunities for learners to experience the full variation of ways in which a given learning concept is applied across different cases.
- Principle 3: Tough Case Time Compression **–** increase practice with complexities of a work domain, by fast-forwarding through or skipping scenario activity between demanding events.
- Principle 4: Case-Proficiency Scaling – maintain training at the edge of the zone of proximal development (note that mentoring is one way of ensuring explanation, etc., is appropriate to the learner's level of proficiency).
- Principle 5: Complexity Preservation – learners should practice in varied contexts; at boundaries of current knowledge and skills; while accessing knowledge when it is useful/needed; and while, to the extent able, exercising advanced skills such as anticipatory thinking, considering the implications of the current situation for the future, constantly updating and reconfiguring understanding "on the fly," and juggling priorities and goal-conflict resolution.
- Principle 6: Active Reflection – help learners to reflect on their current understanding of the problem space, connect what they experience with prior incidents, and consider what they have yet to learn and understand well.

Recommendations for Future Research

Significant research has examined CCS, but much remains to be done. In the CCSRF, proficiency, expertise, and their acquisition are depicted at a high level, as a process of adaptation and evolution in response to exposure to complexity in the work domain. It is important to note that the depiction is not high level because we believed a high-level depiction would be easy for readers to comprehend. Rather, many of the details that might lead to a more intricate representation are lacking. Thus, the CCSRF highlights that there is still much about how CCSs develop that is not well understood.

For example, we do not know how, when, or why cognition might qualitatively change across dimensions such as macrocognitive skills and cognitive mechanism adaptations. Similarly, we do not understand effects of manipulations such as withholding exposure to complexity on the proficiency acquisition trajectory. As additional examples, we know CCSs depend on a base of rich, heavily interconnected knowledge. However, we know little about how to support the development of knowledge that grows to be rich, heavily interconnected, and broadly useful versus compartmentalized, rigid, or overly simplified. Similarly, we understand that basic cognitive mechanisms interweave to produce macrocognitive capabilities, but we know little about how to support actively the initiation and growth of those capabilities. On a related note, we do not know the relative benefit of training and practice focused on specific cognitive mechanisms versus on the macrocognitive skills to which those mechanisms contribute. More generally, the framework highlights the need for research on how CCS learning differs along different phases of the continuum.

The six principles listed in the section above and others like them represent important progress toward understanding how to support and optimize CCS acquisition. Research is required, however, to establish the value of such guidelines and to develop competency assessment and development strategies that put them into practice. In addition, research is needed to both evaluate and evolve methodology for assessing and developing CCS. In support of that research, we need paradigms, measures, and access to instrumented complex environments, both synthetic and operational. In addition, we need longer-term access to learners in complex work domains (i.e., not just Soldiers during their enrollment in training and education courses). Finally, we need wider acceptance of the validity of research methods and paradigms that are suited to the study of complex systems.

Future research should also be conducted to validate and advance the CCSRF. In particular, future research should demonstrate the use of the CCS framework in the analysis of specific cognitive skills performed in complex operational domains, such as the anticipated future multi-domain operating environment. Demonstrating the framework would necessitate the identification of the particular dimensions, objects, and inter-relations for the complex skill under examination. Utilizing the CCS framework in this manner would demonstrate whether the framework applies to an operational setting where a CCS is required to complete a complex task. Future research could validate the conceptual model by employing a cognitive task analysis, then mapping the results of the cognitive task analysis against the framework. Findings from this type of research effort would enable the refinement of the CCS framework. A second recommendation for future research is to confirm the proposed definitions. Follow-on research should ensure the definitions presented here are concise and unambiguous enough to be useful for both practitioners and researchers.

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Appendix A

LITERATURE REVIEW RESULTS IN SUPPORT OF DEFINING COMPLEX COGNITIVE SKILL

Relevant definitions found in the literature are organized below into seven themes and subthemes. They are followed by a discussion of two major philosophical stances on science and research and their implications for defining complex cognitive skill.

I. Defined based on Cognitive Process Characteristics

IA. Defined based on Knowledge Comprehension Requirements Relative to Cognitive Capacity	
Skill that depends on the use of rich, complex knowledge structures, where complex knowledge is defined as an extensive network of interconnected schemata.	Borko & Livingston (1989)
Skill that depends on knowledge representations of a complex concept, system, process, or environment, the comprehension of which places high demands on human cognition and information processing capacity. Knowledge representations are complex if they: • Have many nested steps, variables, or simultaneous processes • Are formalized at a high level of abstraction with a high semantic distance between concept and its symbolic representation • Are inconsistent with prior knowledge or common sense • Are ill-structured and their form depends on the states of co-occurring concepts Concepts, systems, etc. are complex if they are or behave in ways that are: • Abstract (vs. concrete), continuous (vs discrete), simultaneous (vs sequential), organistic (vs mechanistic), interactive (vs separable), conditional (vs universal), or nonlinear (vs linear). • Plus, according to Wulfeck et al. (2003): Multi-variate (vs univariate), continuous (vs discrete), dynamic (vs static), uncertain (vs certain), ambiguous (vs unique)	Feltovich, Spiro, & Coulson (1988) Feltovich, Coulson, & Spiro (2001) Wulfeck, Wetzel-Smith, & Dickieson (2003)
An ability to use knowledge about relationships, levels, and emergent properties in a complex system to: • think about the properties of the whole system and • understand causality that results from multiple interacting and often indirect factors, where *complex systems* are systems consisting of multiple interacting elements and levels, the aggregate effects of which are emergent and not fully predictable.	Hmelo & Azevedo (2006); Hmelo, Marathe, & Silver (2007); Hmelo & Pfeffer (2004)
Complex cognitive skill involves multiple processes, multiple strategies, and multiple pieces of complex knowledge used in parallel to generate viable solutions.	Mumford, Friedrich, Caughron, & Byrne (2007)

- Knowledge representations are case-based and complex (consisting of information about goals, outcomes, critical causes, contingencies, and restrictions), utilizing significant working memory capacity.	

IB. Defined based on Information Processing Requirements Relative to Cognitive Capacity	
Complex cognition is the use of a combination of lower level mental processes to synthesize incoming information and derive new information for the purpose of making decisions, solving problems, or planning actions.	Funke (2010; citing Knauth & Wolf, 2010)
Complex cognition involves a multitude of cognitive processes interacting with one another and with noncognitive processes (e.g., emotions) to derive new information for the purpose of solving problems, making decisions, and planning actions.	Knauth & Wolf (2010)
Skills requiring a large amount of cognitive processing, placing high demands on working memory.	Gillie & Broadbent (1989)
Skills performed in association with a high cognitive load. Cognitive load is high when there is a large number of interacting, unintegrated elements to be processed in working memory, where the size and number of elements will vary by level of expertise. Tasks that consist of many elements for a novice may be conceptualized by experts as having very few chunked or otherwise integrated (within a schema) elements.	van Merrienboer, Kester, & Paas (2006)
Skills/tasks that require coordinating more than one dimension of variation (e.g., determining the best value among differently sized and priced containers).	Wulfeck, Wetzel-Smith, & Dickieson (2003)

IC. Defined Based on Difficulty to Learn	
Skill that takes a long time to learn and continues to improve over years of practice.	Brand-Gruwel, Wopereis, & Vermetten (2005)
Skills that take a long time to learn and are only truly performed well by experts.	Ward et al., 2018
Skills that are difficult to learn.	Wulfeck, Wetzel-Smith, & Dickieson (2003)

ID. Defined in Terms of Integrated Cognitive Processes	
Skills that are adapted to complex performance contexts, frequently characterized by ill-defined goals. They encompass multiple more basic mental activities and are emergent phenomena, emerging from the more basic activities and situational constraints.	Klein et al. (2003)

Complex cognition is defined "as a label for a perspective on psychological processes that searches for an integration of various cognitive processes needed for a smart course of action" (p. 212) A holistic way of considering cognition.	Schmid, Ragni, Gonzalez, & Funke, 2011)
Skills that adapt to the dynamics of complex work or a complex work environment.	Ward et al. (2018)

II. Defined Based on Task Characteristics	
Skill used to perform tasks that have a high: • Information load, • Information diversity, or • Rate of information exchange	Campbell (1988; citing Schroder, Driver, & Streufert, 1967)
Skill used to perform tasks that have: • Multiple potential ways (i.e., paths) to arrive at a desired end-state • Multiple desired outcomes (i.e., end states) to be attained • Conflicting interdependence among paths to multiple outcomes • Uncertain or probabilistic links among paths and outcomes	Campbell (1988)
Complexity is produced by objective task characteristics including: transparency, time variance (dynamic, static), the number of information cues, cue intercorrelations, cue reliabilities, cue validities (i.e., task predictability, function forms (i.e., linear, curvilinear, stochastic, deterministic etc.)), and feedback (delayed or immediate). Complexity is produced by a system structure that includes non-linear and noisy relations between inputs and outputs. This definition holds across levels of performer experience; the authors propose that, even for experts, "certain objective task characteristics of a CDC [*complex dynamic control*] task may produce highly erratic and damaging outcomes" (p. 38).	Osman (2010)
Skill used to perform tasks that are complex, i.e., that have a large problem space, as measured in terms of the number of alternatives or the number of possible system states or action choices.	Quesada, Kintsch, & Gomez (2005)

III. Defined in Terms of What They Are Not	
If training conditions have fewer than four dynamic operational variables (terrain, time, military [threat], and social [population]) to consider, the training is not considered complex.	U.S. Department of the Army (2017a)
Simple cognition is defined as "a term that describes isolated capacities of single psychic functions like perception, memory, and thinking without reference to other functions" (p. 212); Klein's description of *microcognition* (Klein et al., 2003).	Schmid, Ragni, Gonzales, & Funke, (2011)
Systems that are predictable and knowable are not complex and, by inference, interacting in and with them does not require the adaptation of cognition into complex cognitive skill. - It is not complex if the domain or system is ordered and causes and effects are "generally linear, empirical in nature, and not open to dispute. Repeatability allows for predictive models to be created." (p. 468)	Kurtz & Snowden (2003)

- It is complex if stable cause-effect relationships exist in the domain or system but may not be fully known or may be known by a limited group of people. …Relationships are separated over time and space such that they are difficult to fully understand" (p. 468), but nonetheless understandable.	
Systems that are complicated are not complex. - Kurtz and Snowden consider the *knowable* realm to encompass *complicated* and *simple* work, tasks, and skills. If something is knowable but requires time and energy to find out about, they consider it to be complicated, not complex. "Ferraris are complicated machines, but an expert mechanic can take one apart and reassemble it without changing a thing" (Snowden & Boone, 2007, p.5).	Kurtz & Snowden (2003) Snowden & Boone (2007)

IV. Defined as Cognitive Adaptation to Conditions that Produce Emergence and Unpredictability	
Complex skills are skills that adapt to the dynamics of complex work or a complex work environment.	Ward et al. (2018)
The system or task/work is complex if agents' interactions with the system constantly modify the nature of the constraints on what the system can do and does. While they are constrained, "the constraints are loose, or partial, and the nature of the constraints (and thereby the system) is constantly modified by the interaction of the agents with the system and each other; they coevolve" (p. 225). The co-evolutionary nature of agents in the system and the system means that their behavior is inherently never completely predictable.	Snowden (2011)
Complex systems are described in terms of interactions among their elements that produce an emergent 'whole' that cannot be entirely predicted by knowing the parts.	Paries (2006)
Skill required for performing effectively with or in a complex system, task, or environment (i.e., context), where context is complex if it: • Operates at multiple distinct levels of organization, • Involves non-linear interactions among the system's elements including positive and negative feedback loops, • Is describable in terms of interactions among its individual elements and macroscopically in terms of system-level patterns, and • Is capable of producing system-level patterns that emerge without any force explicitly striving for the pattern, through the self-organized activity of many interacting elements.	Goldstone & Wilensky (2008)
Characteristics of a complex work environment: - Dynamic speed of change, compression of time - Daily challenges are unpredictable - More unknowns than knowns	Cohen (2017)
Large-scale combat operations are characterized by - Multiple ongoing interrelated activities, including in both the information and physical-effects domains - Chaos/lack of order, uncertainty, and ambiguity	U.S. Department of the Army (2017b), FM 3-0

- Rapid turns of events; extreme levels of dynamism - The potential for severe consequences at the personal, organizational, and national levels, which adds fear to the mix of variables - Reduced predictability and mental preparation as a result of a departure from the norms of civilized society, such that a much wider range of actions may be encountered, including brutal and lethal actions.	
Characteristics of a complex work environment: - Entities with which one interacts are distributed, interactive, and behave largely independently of one another - Composed of interacting layers of many types of interactive elements affected by a vast number of interacting variables operating within different types of organizations, cultures, operations, and conditions.	U.S. Department of the Army (2017c), FM 3-12
Conditions defined by variation in and interaction among political, economic, social, information, infrastructure, physical, and time (PMESII-PT) variables, of which there are many of each type.	U.S. Department of the Army (2012), ADRP 5-0
Environments characterized by unpredictable and unexpected motivations and actions, networked global threat organizations, and a dynamic threat landscape in which threats are embedded and camouflaged in civilian activities and populations. In other words: unpredictable, heavily interconnected and interactive, poor transparency and feedback, and ambiguous, disguised signals.	U.S. Department of the Army (2017d)
"Complex is defined as an environment that is not only unknown, but unknowable and constantly changing. The Army cannot predict who it will fight, where it will fight, and with what coalition it will fight." (p. iii) The interaction of conditions, circumstances, and influences affect the choice of capabilities employed. Some of the factors affecting outcomes in complex operational environment include: - Increased velocity and momentum of human interaction and events - Capable elusive enemies - Potential Overmatch - Proliferation of weapons of mass destruction - Spread of advanced Cyberspace and counter-space capabilities - Dense Urban Areas- "Rise of Mega cities and complex terrain" - Technology Transfer - Ubiquitous media	U.S. Department of the Army (2014)
Conditions that feature variable tactical scenarios, levels of involvement across organizational levels; and physical environment. Conditions that present ethical, mental, and physical challenges that must be handled under stressful and ambiguous performance conditions.	U.S. Department of the Army (2016), FM 7-0

The definitions listed above can also be conceptualized as supporting two different, contrasting stances on how to define and study complex cognitive skill. These are presented directly below and are followed by a short summary of their differences.

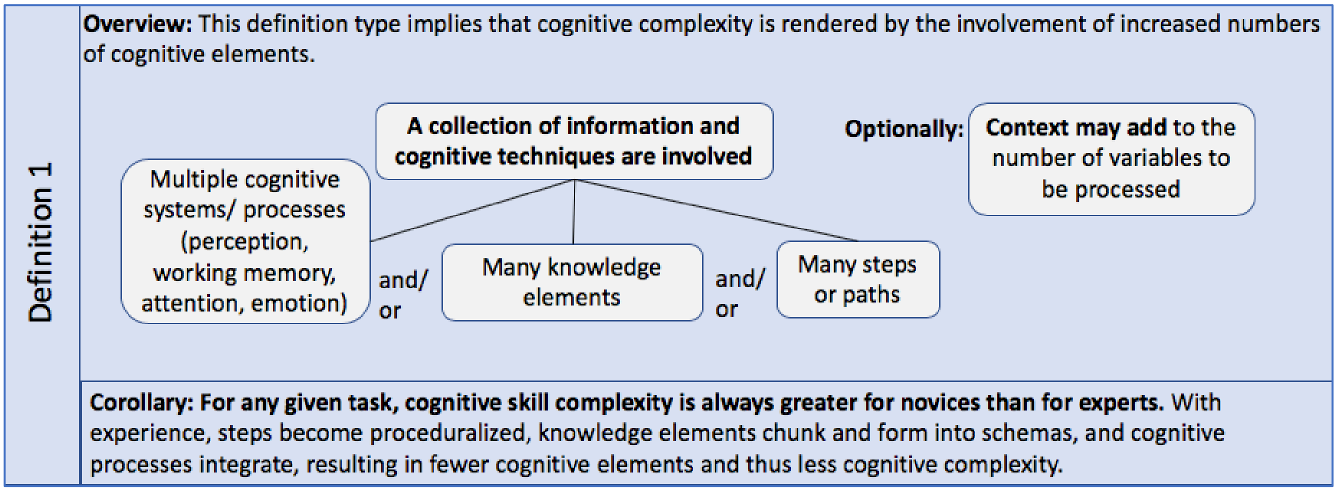
V. Defined According to the Information Processing Tradition

A definition that is consistent with the *information processing paradigm* would specify complex cognitive skill in terms of elements that can be controlled and manipulated, such as cognitive processes, knowledge elements, and the steps involved in performing a task, as shown in the figure directly below. The information processing paradigm goes back to at least 1968 (Atkinson & Shiffrin, 1968) and remains a dominant influence on research and theory in Cognitive Psychology. The paradigm was designed to support the study of cognition in controlled laboratory studies, a prerequisite for the advancement of science according to positivist and critical rationalist epistemologies (e.g., Popper, 2014). Accordingly, its goal is to minimize complexity so that specific effects of specifically defined variables can be tested in a controlled setting.

Consistent with this approach to research, Candidate Definition 1 presented on Page 3 describes complexity in terms of variables that can be tested in controlled laboratory studies. For example, it specifies knowledge in terms of amount and type, internal systems in terms of the number employed and whether or not they interact, and the task in terms of its length (number of steps). A corollary to this way of defining complex cognitive skill is that as a person gains proficiency in a given task or work domain, the task or work becomes less complex. This is because as experience is gained, knowledge and procedural elements tend to become chunked and proceduralized, respectively (e.g., Anderson, 1982), and thus become fewer in number.

It can be argued that removing the thing you want to study (e.g., complexity) by means of experimental control is counterproductive to studying it. Further, it may be impossible to specify a testable hypothesis for traditional experimentation when the effect of manipulating an independent variable is emergent and unpredictable, as it would be in a complex system from which complexity has not been removed.

This type of experimentation is thus generally incompatible with complex systems as defined in the complex-systems science literature, i.e., as emergent, nonlinear, and at least somewhat unpredictable (e.g., Heylighen, Cilliers, & Gershenson, 2007; see also Snowden [2011] and Paries' [2006] definitions listed above [p. 8]). On the other hand, language that represents or otherwise connects to the information processing paradigm may be useful in a definition of complex cognitive skill. In particular, it may provide a means for the many researchers who conduct basic cognitive research to relate to the construct and contribute to the associated research base.



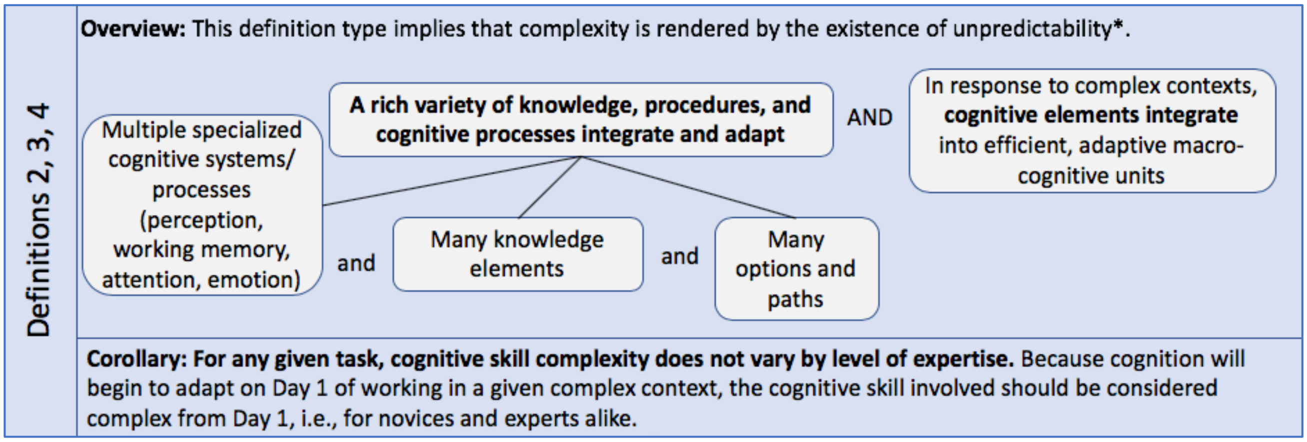
VI. Defined According to the Naturalistic, Macrocognitive Tradition

In the Macrocognitive view, cognitive elements (e.g., knowledge, information stores, and cognitive processes) are not separable in reality and so cannot be meaningfully separated for study. In this view, cognitive elements co-evolve (influence how one another evolves) and integrate with one another in ways that are adaptive to the situation at hand. Their integrated adaptation to the situation or a given task or work domain becomes increasingly tuned as experience is gained.

For even basic and simple tasks, a certain amount of cognitive adaptation is required. For example, Anderson's (1993) ACT-R theory describes declarative and procedural knowledge elements as becoming integrated so that a person can perform quickly and fluidly without pausing to retrieve the next step from memory or to think about how to execute it. Automaticity theory (Shiffrin & Schneider, 1977) describes a level of fluency that goes beyond proceduralization to where almost no thought at all is required.

Declarative and procedural knowledge integration and automatization, however, can occur during the learning of any task, no matter how simple. According to the Macrocognitive view, what makes a cognitive skill complex is not the use of multiple cognitive elements or their chunking, proceduralization, and automatization. As shown in the figure below, there must also be a complex environment placing stress on cognition and requiring a type of cognitive skill that can support effective interaction and performance in that complex environment, where a complex environment is one that is difficult to predict, not fully knowable, dynamic, and characterized by emergence and nonlinearity (e.g., Heylighen et al., 2007). Additional stressors such as time pressure and high stakes mean that cognitive adaptations must be especially well honed to the complexities of the work.

Cognitive skill that can support performance in a complex environment is an emergent, highly adapted, multi-threaded, richly intertwined form of cognition. This type of cognitive skill that is adapted to the demands of a complex work domain is an emergent form of cognition referred to as macrocognition (Klein et al., 2003) and is considered a complex cognitive skill in the macrocognitive tradition. A corollary to this way of defining complex cognitive skill is that as a person gains proficiency in a given task or work domain, their cognitive skills adapt to the complexities of that task or domain and become part of the complex dynamic. In contrast with the microcognitive information processing view described above, the task or work does not become less complex as experience is gained.



A summary of the differences between the two dominant stances/traditions:

Below, we summarize the differences between the information processing and macrocognitive traditions and the implications of those differences for defining complex cognitive skill.

- The information processing tradition is focused on reducing cognition into its lowest level elements so that they can be independently manipulated, controlled, and studied in experimental research. This tradition supports basic research to study cognition, whether simple or complex.
- The macrocognitive tradition is focused on the integration of cognition into higher-level cognitive capabilities and the adaptation of those higher-level capabilities (e.g., sensemaking) to work and environmental demands and stressors. Researchers who study macrocognition use experimental methods but rely heavily on naturalistic methods of research that support studying cognitive adaptations over time to realistic demands and stressors. This tradition supports applied research to study complex cognition.

These differences translate into different ways of conceptualizing complex cognitive skills:

- Researchers who work within the information processing tradition will likely want to define complex cognitive skills in a way that supports pulling apart a skill's various elements and reducing those elements down into the lowest level of granularity possible.
- Researchers who work within the macrocognitive tradition will object to pulling apart and reducing cognitive skills. They view cognitive skill as an emergent property that is lost by reducing it into its parts or removing it from the complex environment that shapes it. They will be more likely to accept a definition that describes complex cognitive skill in holistic, versus reductionist, ways.

Examples of definitions from above that align with each tradition are as follows:

- Consistent with the information processing tradition: *Complex cognitive skill involves multiple processes, multiple strategies, and multiple pieces of complex knowledge used in parallel to generate viable solutions* (Mumford, Friedrich, Caughron, & Byrne, 2007)
- Consistent with the macrocognitive tradition: *Complex skills are skills that adapt to the dynamics of complex work or a complex work environment* (Ward et al., 2018) and *an ability to use knowledge about relationships, levels, and emergent properties in a complex system to think about the properties of the whole system and understand causality that results from multiple interacting and often indirect factors* (Hmelo et al., 2007)

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Appendix B

ANNOTATED BIBLIOGRAPHY
OF ARTICLES ABOUT COMPLEX COGNITIVE SKILLS
AND THEIR ACQUISITION

Borko, H., & Livingston, C. (1989). Cognition and improvisation: Differences in mathematics instruction by expert and novice teachers. *American Educational Research Journal*, *26*(4), 473-498.
Cited by 992.

Overview: This is an observation- and interview-based comparison of teaching differences between expert and novice teachers.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:
- "…we do not yet know enough about the development of [this complex cognitive form of] expertise to confidently design…preparation programs to give the most appropriate opportunities for knowledge and skill development" (p. 492).

Findings/Proposed Complex Cognitive Skill:
- Expert teachers had elaborate, interconnected knowledge structures referred to as *schemas* that come in three different forms: *scripts*, *scenes*, and *propositional (declarative) knowledge structures*. Novices lacked these knowledge structures.
- Expert teachers: Anticipated student problems, saw interconnections across their curriculum, and improvised in response to student questions while keeping the discussion linked to lesson goals.
- These expert capabilities were characterized as grounded in teachers' knowledge structures; specifically, in "an extensive network of interconnected, easily accessible schemata" (p. 485).

Borders, P., Polander, N., Klein, G., & Wright, C. (2015). ShadowBox: Flexible training to impart the expert mindset. *Proceedings of the 6th International Conference on Applied Human Factors and Ergonomics and the Affiliated Conferences* (pp. 1574-1579). Las Vegas, Nevada: Applied Human Factors and Ergonomics.
Cited by 4.

Overview: ShadowBox is a scenario-based technique that trains people to be experts in a domain without requiring the real-time attention of experts (cognitive task analyses are done beforehand). Trainees are asked to rank (and justify) pre-determined sets of options given to them in realistic scenarios (trainees are more motivated and demonstrate better learning when applying KSAs in realistic scenarios), then compare their rankings/rationales to expert rankings/rationales. ShadowBox can also be used to diagnose trainee mindset by comparing results from established mindset diagnostic measures to identified organizational mindsets (e.g., "good stranger" mindset for social military-to-civilian encounters)

Claims Requiring Further Research, Research Gaps, and Research Suggestions:
- How realistic are the scenarios and how does the training translate to real-world performance?
- Authors claim that if trainee mindset is aligned with an organization's mindset, trainee could lose motivation because he or she is learning something they already know, but it also seems that the trainee could be encouraged because they find that they're a good fit with the organization in a deep way (not just in terms of technical information).

Findings/Proposed Complex Cognitive Skill:

- Rules, procedures, and declarative knowledge are useful for well-defined domains, but not as much for dynamic domains. Experts set themselves apart by identifying big-picture patterns, critical cues, and missing information in complex domains with uncertainty, ambiguity, shifting goals, time pressures, and ill-defined tasks.
- Expertise is developed through "deliberate practice, extensive experience, diagnostic and timely feedback, thoughtful review of previous experiences, and lessons learned from mistakes. Training for novices, then, will be most effective when it serves as a platform for enhancing perceptual and pattern-recognition skills, provides useful feedback, facilitates the development of higher-level cognitive skills, and exposes novices to a variety of relevant experiences within the domain." (p. 1576)

Boulton, L. (2016). Adaptive flexibility: Examining the role of expertise in the decision making of authorized firearms officers during armed confrontation. *Journal of Cognitive Engineering and Decision Making*, *10*(3), 291-308.
Cited by 8.

Overview: Boulton conducted a cognitive task analysis of the situation assessment and decision making of authorized firearms officers (AFOs) during armed confrontations. Qualitative analyses of interview data from 12 expert (7 to 21 years of experience) and 11 novice (10 to 48 months of experience) firearms officers revealed that AFOs, as they gain expertise, learn to flexibly and confidently adapt their responses to situational changes in high-stress and cognitively demand situations. Novice AFOs, in contrast, tend to follow a sequence of standard operating procedures (SOPs) without adapting their responses to variations in the situation until faced with an immediate threat to life, at which point the adaptation is a panicked defensive response.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:
- Citing Klein's *Cognitive Transformation Theory* (Klein & Baxter, 2009), the authors propose that adaptive expertise requires the acquisition/development of:
  - Mental models,
  - Sensemaking skills for recognizing when mental models conflict with the current situation, and
  - The ability to revise or reject mental models in response to situation assessments.

Findings/Proposed Complex Cognitive Skill:
- Both groups formed and tested mental models and used schemas to judge typicality and recognize anomalies; both groups recognized situational cues that signaled a need to adapt.
  - Expert AFOs "understood the interactions between the cues and the unfolding incident and responded by quickly and intuitively adapting appropriately, whereas novices followed SOPs even when doing so was counterproductive unless faced with an immediate threat to their life or a more senior or experienced AFO first confirmed their deviation. Experts could also generate a larger set of potential incident developments.
- Adaptive flexibility sets novice and expert AFOs apart. It is based in:
  - Knowledge of underlying principles that govern dynamics of situations in the domain,
  - Recognition of those principles at play in a given situation, and
  - Mental modeling to connect and explain the situation and to evaluate different ways (in light of the governing principles) the situation may unfold.

Brand-Gruwel, S., Wopereis, I., & Vermetten, Y. (2005). Information problem solving by experts and novices: Analysis of a complex cognitive skill. *Computers in Human Behavior, 21*(3), 487-508.
Cited by 361.

Overview: Computer interactions and verbal communications of expert and novice students (in final year of PhD vs first-year undergraduates) were observed and captured during an information search and synthesis task.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:
- The authors recommend training *metacognitive skills* (regulation, specifically) via *cognitive apprenticeship*, explaining that the method "intends to bring internal (expert) cognitive processes out into the open."
- The authors cite van Merriënboer's hypothesis that a complex cognitive skill can become a generalizable skill if it is trained in as many domains as possible. A counter-hypothesis is that the skill will specialize to each domain in which it's trained and remain domain-specific.
- What skills generalize/transfer across domains?
- How to develop transferable skills so they transfer?

Findings/Proposed Complex Cognitive Skill:
- Information Problem Solving is a complex cognitive skill (because it takes time to acquire). It consists of a number of other skills and subskills, some of which on their own might not be considered complex.
- Expert-novice differences highlight aspects of the skill that make it complex.
    - Experts spent more time defining the problem relative to other activities and more often:
        - activated prior knowledge,
        - elaborated on scanned content by relating it to existing knowledge, and
        - regulated their process.

Branlat, M., Morison, A., & Woods, D. D. (2011). Challenges in managing uncertainty during cyber events: Lessons from the staged-world study of a large-scale adversarial cyber security exercise. *Human Systems Integration Symposium*, Vienna, VA, October 25-27, 2011.
Cited by 11.

Overview: The authors describe lessons learned from a large-scale adversarial cyber security exercise in which they studied challenges and management of uncertainty faced by network analyst attackers and defenders. The study discusses the perspective of each team for attacking and defense and uncovered a "chasing game" relationship. The attacking team has the advantage of a window of time during which they can take any variety of actions before being detected by the defending team. The defenders, on the other hand, never know when an attack will or occur, what form it will take, or what to expect next. The defenders are continuously dealing with high levels of uncertainty while attempting to anticipate the attacking team's next actions, even as the attackers may be trying to decide their next move and otherwise "fumbling in the dark".

Claims Requiring Further Research, Research Gaps, and Research Suggestions:
Observed cognitive work of cyber defense team:
- Anticipation: understanding and making projections about what the other side is targeting. In cyber defense, anticipation involves:
    - Knowing about vulnerabilities, patterns of attack, and the evolving intent of the adversary.
    - Anticipating how adverse events might evolve
- Balancing conflicting goals; understanding and managing the impact of the defense response on production goals
- Understanding and managing the impact of adverse effects on the system

- Strategic knowledge, e.g., about how to draw out attackers
- Anomaly detection based on mapping indications against a situation mental model
- Continuous adapting of mental model of the attack and response strategies as new details are detected
- Manage large amounts of incoming information

Champion, M. A., Rajivan, P., Cooke, N. J., & Jariwala, S. (2012). Team-Based Cyber Defense Analysis. *2012 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support*, March 6-8, New Orleans, LA.
Cited by 35

Overview: The research team conducted a cognitive task analysis of the work of cyber defense, followed by a preliminary study conducted in a synthetic cyber defense task environment called *CyberCog*. Naturalistic research consisted of interviews with cyber security analysts and observation of the Air Force Academy's Cyber Defense Exercise. Assessment of the interview and observation data revealed three potential sources of team performance breakdown in cyber defense operations: overall team organization, team communication, and the amount of information to be processed by the team and individual analysts. These three issues were assessed as surfacing in the study, based on measures of subjective situation awareness, subjective mental workload, and attack-path report accuracy of eight three-person teams.

Claims Requiring Further Research, Research Gaps, and Research Suggestions: Too few details about the conduct of the preliminary study were provided to judge the validity of the findings.

Gaps/Research Suggestions: The authors point out that cyber defense is a new form of work and that there is therefore much to learn.

Findings/Proposed Complex Cognitive Skill: The authors propose that cyber analysts need individual and team situation awareness, noting that team situation awareness calls for a team to adapt to, maintain awareness of, and respond to the situation at hand. Their research revealed three obstacles to good team situation awareness. These obstacles suggest that analysts would benefit from:

- A mental model of the complex cyber defense and network management organizations within which they operate.
- Knowledge about how to communicate effectively with one another under conditions of time pressure and a very high information load
- Strategic knowledge that facilitates the handling of an extremely high information load (In the Cyber Defense Exercise, which featured only one adversary, each analyst might have to deal with hundreds to tens of thousands of security events in a given hour)

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences, 14*, 161–199.
Cited by 822.

Overview: Chi is well known for her work on expert-novice differences going to back to at least 1981. In this paper, she extends that body of work and in particular her work on the development and perseveration of misconceptions. She draws on her prior research demonstrating that certain types of misconceptions are more easily and reliably corrected than others and investigates a hypothesis about the characteristic(s) of knowledge-to-be-learned that seem to determine whether misconceptions will be easily corrected or persist: Specifically, she hypothesizes that misconceptions about complex phenomena tend to persist when phenomena derive coincidentally or emergently from interactions and dynamics, such as in the case of diffusion. In contrast, when phenomena follow directly from system processes and functional goals, misconceptions tend to be easily corrected.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Chi claims that misconceptions are formed because students don't understand emergence. They assign specific, direct causes to emergent and indirect outcomes and turn nonlinear relationships into linear relationships. She suggests that students need a representation of the problem space (a schema) that recognizes emergence (complexity). To that end, she says "if we can help students build a general structure or schema of emergence first (in the context of using simulations and role-playing activities), then presumably learning, in the sense of assimilating and integrating new knowledge with existing knowledge, can be more easily undertaken because the relevant cognitive structure will already have existed" (p. 194).
- "presumably such learning can transfer more readily because the attributes of an emergent schema will apply to many emergent processes" (p. 194).

Findings/Proposed Complex Cognitive Skill: Chi concludes, based on the synthesis and evolution of her empirical work, that students tend to rely on their commonsense understanding of direct processes to understand both types of systems and dynamics, when that perspective only maps well to the latter type of system. Students' misrepresentation of processes as direct when they are actually emergent interferes with their ability to understand feedback. In particular, students must first change the way the problem space is represented before they can correct the misconception.

Cyber Intelligence Task Force (2015). *Cyber intelligence: Preparing today's talent for* tomorrow's *threats*. Retrieved from https://www.insaonline.org/cyber-intelligence-preparing-todays-talents-for-tomorrows-threats/

Overview: Reviews existing competency frameworks for cyber intelligence analysis and proposes a framework that merges the two and addresses a hypothesized weakness in them, which is the absence of separate tracks for technical and analytic knowledge and skill observed in a cognitive task analysis by a single set of authors (Hutchins, Card, and Pirelli) in 2004.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- The competency frameworks discussed do not **address the need to learn and use the different categories of knowledge and competency in integrated ways**. For example, at what point should the technical competencies be learned in the context of analysis and associated analytic competencies? (Competency and Training Gap)
- Proficiency in complex competencies is only acquired over years of experience, and **continued support for their acquisition** is not addressed by the frameworks in this document. The document reads as though competencies are fully acquired during initial training and then just need to be refreshed ("an undergraduate or even a graduate degree is insufficient to stay current"). Curricula and programs are described in the *Entry Level Analyst* section; however, the *Continuing Education and Respecialization* section is sparse on detail.

Findings/Proposed Cyber Intelligence Competencies: See proposed competencies in Column 1 of Table 1. These are derived from:

- Carnegie Mellon University's Software Engineering Institute (SEI) surveyed cyber intelligence programs in the Cyber Intelligence Tradecraft Project (CITP) and identified the following "teachable skills", or core competencies shown in Column 2 of Table 1.
- National Institute for Standards and Technology (NIST) National Cybersecurity Workforce (NCW) Framework, "developed through collaboration with government and the private sector" and shown in Column 3 of Table 1.

***Table 1*. A comparison of three proposed sets of cyber operations competencies.**

Proposed by INSA	Proposed by CMU SEI	Proposed by NIST
Technical competencies (knowledge about hardware and software used in information processing and communications)	Computing fundamentals (networks/networking, operating systems, databases, programming, scripting, data mining)	
	Information security (vulnerability assessment, cryptography, technical architecture, information architecture, network defense, incident response	
	Technical exploitation (malware, penetration testing, social engineering, web services, wireless networks, web applications)	
Analytic competencies (foundations of strategy, critical and systems thinking, reasoning and logic, problem solving, and decision making	Critical thinking (problem solving, diversity of perspective, problem definition, big picture/scope management),	Threat analysis (Assesses and identifies the capabilities and activities of cyber criminals, produces findings that support law enforcement and counterintelligence),
		All source intelligence (Draws insights from information drawn from variety of sources),
		Exploitation analysis (Analyze information to identify vulnerabilities and potential for exploitation)
Communication and organizational (clear and effective communication and reasoning, project management skills)	Communication and collaboration (technical writing, writing for leadership, debating skills, knowing your audience, conflict resolution, attention to detail, assimilate new information)	
Knowledge management (informatics; knowledge management and information science foundation for planning and organizing data collection)	Data collection and examination (research methodologies and applications, validation/verification),	
Contextual domain competencies (sector-specific, national/regional, and/or sociocultural foundations		Targets (apply current knowledge of regions, countries, non-state entities, and/or technologies)

for analyzing complex problems; identifying key actors and roles; assessing perceptions, interests, and intentions; sensemaking; drawing inferences; and discerning situational influences.)		

D'Amico, A., Whitley, K., Tesone, D., O'Brien, B., & Roth, E. (2005). Achieving cyber defense situational awareness: A cognitive task analysis of information assurance analysts. In *Proceedings of the human factors and ergonomics society annual meeting* (*Vol. 49*, pp. 229-233). Los Angeles, CA: Sage.
Cited by 107

Overview: A cognitive task analysis of the work of information assurance (IA) analysts is described. The authors map IA analysts' cognitive work to Endsley's three stages of situation awareness (SA), perception, comprehension, and projection, and to the three stages of cognitive data fusion specified by the Joint Directors of Laboratories (JDL), detection, situation assessment, and threat assessment. The authors also discuss the cognitive challenges IA analysts face such as processing massive amounts of data, fusing complex data, building specific site knowledge, and maintaining multiple mental models.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- This research produced a details description of each of multiple cognitive work activities involved in IA. The authors interest is in determining how to best support those activities using visualization techniques.
- Their work additionally allows training to be mapped to the activities and challenges of IA work.

Findings/Proposed Complex Cognitive Skill:
The authors conclude that IA analysts use following cognitive activities to gain SA about a potential cyber-attack:

- Correlate data to find patterns of suspicious and anomalous behavior,
- Create, modify, and refine mental models of attacker's identity and current and future actions,
- Test hypotheses based on the created/active mental model, and
- Project potential future actions, based on the created/active mental model.

D'Amico, A., & Whitley, K. (2008). The real work of computer network defense analysts. In J. R. Goodall, G. Conti, and K. L. Ma (Eds.), *Proceedings of the Workshop on Visualization for Computer Security* (*VizSEC 2007*; pp. 19-37). Boston, MA: Springer.
Cited by 97.

Overview: The authors describe their cognitive task analysis (CTA) of the work of computer network defense (CND) analysts. Their results include a description of the process of distilling and synthesizing large amounts of data in order to identify and respond to incidents and a description of the tasks performed by different CND personnel. Findings are used to suggest visualizations that could facilitate challenging aspects of CND analysts' information processing work.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- The authors propose visualizations to support this information-intensive and challenging work. The visualizations and other types of support, e.g., training support, require investigation and refinement.

Findings/Proposed Complex Cognitive Skill:
The authors represent CND work as a cyclical process that follows Endsley's three-stage model of situation awareness (SA). They map the triage of sensor data and processing of that data into information to the SA stage of Perception (and also refer to it as Detection). They map to the Comprehension (Situation Assessment) stage tasks that involve collecting data from additional sources to investigate patterns, trends, and escalated activity in order to create knowledge products. They map to the Projection (Threat Assessment) stage the deeper and cross-organizational analysis of incidents and incident patterns, consideration of attacker motives and techniques, and the generation of knowledge-based prediction. The authors describe a need for analysts to:

- Be able to map out the system-space and understand how an attack propagated through that space, whether it was successful, and what its effects were.
- Look across time and the system-space to detect anomalies and create a mental model of patterns
- Synthesize across data sources and types

Fautua, D. T., & Schatz, S. (2012). Cognitive readiness and the challenge of institutionalizing the "new" versus "news". *Journal of Cognitive Engineering and Decision Making, 6*(3), 276-298.
Cited by 7

Overview: Despite widespread interest in the concept of cognitive readiness for military personnel, it has been difficult to establish universal standards, terms, and instructional foundations. The authors discuss three related challenges and offer potential solutions for institutionalizing cognitive readiness for the military. First, the authors discuss the difficulty of introducing change into established organizations with established ways of doing things. Yet, cognitive readiness cannot be viewed as an addendum to current training; it should be trained in ways that are responsive to its unique characteristics and should be its own area of study. Cognitive readiness and associated skills need to be seen by military training and education institutions as requiring something different from already established training and education approaches. The second challenge is that these skills may be perceived by the military as "soft skills" that are not critical to combat success. Third, the authors address the tendency to try to train and assess cognitive readiness skills such as decision making in the ways of physically observable skills, such assembling a gun. The authors present a Cognitive Skill-Stance Hierarchy based off the Abstraction Hierarchy developed by Rasmussen (1986) as a framework to guide cognitive readiness training. Third, there must be a commitment to sustain the advances made to institutionalize cognitive readiness training.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- The authors note existing frameworks have been proposed that could be used to guide training suited for cognitive readiness (versus more traditional training methods that they consider to be unsuited). These new frameworks include the observe, orient, decide, act (OODA) loop model, the sense, assess, protect, reflect, respond (SAPRR) model, the critique-explore-compare-adapt (CECA) model, and their cognitive skill-stance hierarchy (CSS hierarchy).
- The authors make the case that experience alone does not develop intuitive decision making and that it can be explicitly and deliberately trained, even if is not easily defined or measured. This was illustrated with the example of a cavalry regiment adapting to unconventional warfare after its commander cancelled traditional training exercises and

replaced them with role-playing, high fidelity scenarios to enhance decision making skills that are relevant to modern military operations.

Findings/Proposed Complex Cognitive Skill:

The table below presents article excerpts describing sets of cognitive skills linked to cognitive readiness by the authors. Each excerpt is accompanied by references to works the authors cite as support. Cognitive skills called out in each excerpt are bolded.

Cognitive Skills Identified as Relevant to Cognitive Readiness *All excerpts below are direct quotes from the article.*	**References Cited as Support**
Achievement of cognitive readiness in somewhat akin to developing *coup d'oeil* or an "intuitive sense of the battlefield"; that is, effective cognitive readiness ultimately manifests as successful **pattern recognition**, **creative adaptability**, and **intuitive decision making** in the field. (p. 277)	Yancy, S. D. (2006). *Adapting professional military education to the current threat* (AU/ACSC/5694/2006-04). Maxwell Air Force Base, AL: Air Command and Staff College, Air University.
Accessing **expertise in sensemaking**, **reading the environmental and human terrains, establishing a baseline**, **detecting anomalies, and anticipating threats** not only enables proactive decision making but also facilitates other macrocognitive skills, such as **intuitive reasoning, adaptiveness, and tactical patience**. (p. 278)	Fautua, D., Schatz, S., Kobus, D., Spiker, V. A., Ross, W., Johnston, J. H., Nicholson, D., & Reitz, E. A. (2010). *Border Hunter research technical report* (IST-TR-10-01). Orlando, FL: University of Central Florida Institute for Simulation and Training.
McMaster's rescripting enabled the development of key cognitive skills, such as **mindfulness, sensemaking, adaptiveness, and intelligent memory**, that promoted better intuitive decision making and overall cognitive readiness (p. 282)	Fahle, M., & Poggio, T. (2002). *Perceptual learning*. Cambridge, MA: MIT Press. Gordon, B., & Berger, L. (2003). Intelligent memory: A prescription for improving your memory. New York, NY: Penguin Books.
…working for the Institute for Defense Analysis, identified 10 competencies as the basis for cognitive readiness: **situation awareness, memory, transfer of training, metacognition, automaticity, problem solving, decision making, mental flexibility and creativity, leadership, and emotion**. (p. 285)	Morrison, J. E., & Fletcher, J. D. (2002). *Cognitive readiness* (IDA Paper P-3735). Alexandria, VA: Institute for Defense Analysis.
The Marine Corps' Training and Education Command (TECOM) has likewise been working to define the standards for cognitive competencies in such areas as **sensemaking, problem solving, adaptability, mindfulness, and attentional control**. (p.277)	Conway, J. T. (2008). *Marine Corps vision and strategy 2025*. Washington, DC: General Admin and Management. Gideons, C., Padilla, F., & Lethin, C. (2008, September). *Combat Hunter: The training continues. Marine Corps Gazette*, pp. 79–84. Small Unit Decision Making. (2011). *US Marine Corps Small Unit Decision Making January 2011 workshop repor*t. Quantico, VA: USMC Training and Education Command.
Possessing competencies in an **adaptive stance, mindfulness, and sensemaking** creates the preconditions for **self-awareness, self-regulation, flexibility**, and effective **intuitive decision making**. (p. 281)	Proposed by the authors of this article.

Feltovich, P. J., Spiro, P. J., & Coulson, R. L. (1988). *The nature of conceptual understanding in biomedicine: The deep structure of complex ideas and the development of misconceptions* (Technical Report No. 440). University of Illinois at Urbana-Champaign: Center for the Study of Reading.
C*ited by 311*.

Overview: The authors draw on their study of knowledge representation and, particularly, medical residents' and professionals' biomedical conceptual knowledge, to propose a general framework for studying the acquisition and cognitive representation of biomedical concepts. The framework addresses the authors' findings about errors in conceptual knowledge and their etiology.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- "If the goal, ultimately, is deep understanding (ultimately "getting it right"), then the desirability in some situations of fundamentally different approaches to early learning is raised.
    - Alternatives might include exposing students to the full complexity of ideas from the beginning, recognizing that their initial feelings of mastery, accomplishment, and satisfaction may suffer temporarily, but that their horizons of understanding may be greater." (p. 5)
- "Another alternative…involves the instructional use of C) relatively simple and understandable pedagogical components, but with a guidance system that at every step of learning highlights the limitations and misleading aspects of these components, as well as the linkages and sources of mutual embellishment among them." (p. 5)

Findings/Proposed Complex Cognitive Skill: "Little is known about the acquisition of the advanced understandings found in expertise

- Or about the best educational methods for fostering them" (p.2).
- Patterns of misconception development and that should be minimized via instructional methodology
- Characteristics of conceptual knowledge that contribute to acquisition difficulty
- Expert mastery of complex conceptual knowledge is dependent on initial learning strategies.
- "When students reason about effects, they miss the connectedness within the system and the complex causal relationships, displaying a reductive bias (Feltovich et al., 1989)" (Hmelo-Silver et al., 2007, p. 309).

Fenwick, T. & Dahlgren, M. A. (2015). Towards socio-material approaches in simulation-based education: Lessons from complexity theory. *Medical Education*, *49*, 359-367.
Cited by 49.

Overview: Simulation-based education in complex domains needs to be more theory-driven. Complexity theory offers ways to use concepts such as emergence, attunement, disturbance, and experimentation, when designing simulations.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Perturbations in the system (e.g., external interruptions, conflicting viewpoints) that force students to deal with discomfort, resist seeking control, and engage in a way that promotes learning (educators can plan the occurrence of these perturbations)
- Reflective activities for students to partake in while a simulation is paused
- How much complexity is too much for a given student (novices likely need less, but how much less)

Findings/Proposed Complex Cognitive Skill:

- "…illness and health are produced through complex, dynamic interactions; therefore clinical judgment and the effectiveness of interventions usually involve irreducible uncertainty" (p. 360)
- Simulation-based education "has been criticized for lacking a robust theory base (Cook et al., 2013). It tends to rest on individualist, mentalist assumptions of learning, such as models of acquire-and-transfer or reflective practice, which have been heavily critiqued in the broader professional learning literature. More contemporary practice learning theories show that learning is collective and is situated in dynamic, emergent webs of activity and materials (Fenwick & Nerland, 2014)" (p. 361)
- Key complexity concepts in simulation-based education
    - Emergence: Diverse elements in a system interact non-linearly and choices lead to changes in the dynamics of the system, creating continuous indeterminacy
    - Attunement: Operators in complex environments need to have a sense of what's happening in the environment via listening, observing, touching, intuiting, etc., especially with other operators. They also need to be aware of the effects of their actions on others and anticipate how they themselves will need to respond (anticipatory action).
    - Disturbance is necessary to "interrupt the tendency to consensus: dissenting voices and the jagged edges of contrasting opinions lead to collective products that are more useful and more insightful" (Davis & Sumara, 2010)
    - Nested systems: Systems can interact in a nested manner (e.g., "surgical practice nested in the organizational structures and various systems of professional groups, each with its own history, routines…"
    - Experimentation creates multiple feedback sources/loops

Fiore, S. M., Ross, K. G., & Jentsch, F. (2012). A team cognitive readiness framework for small-unit training. *Journal of Cognitive Engineering and Decision Making, 6* (3), 325-349.

Overview: A theoretical framework for training team cognitive readiness (TCR) in dynamic environments which consists of perceptual processing, cue recognition, problem solving, decision making, and complex coordinative processes

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Testing relationships between individual and team cognitive processes
- Optimal sequencing of tasks and stress level variations to best prepare small units

Findings/Proposed Complex Cognitive Skill:

- Sense-making at a small-unit level is more important in modern irregular warfare (decentralized and rapid decisions, complex coordination, unpredictable, high-stress, dangerous)
- Effectiveness is an evaluation of performance
- Readiness is potential to perform well
    - Readiness has been defined as the "mental preparation (including skills, knowledge, abilities, motivations, and personal dispositions) an individual needs to establish and sustain competent performance in the complex and unpredictable environment of modern military operations" (Morrison & Fletcher, 2002; p. 1-3, emphasis added).
    - Two types of expertise
        - Routine: Having a large repository of knowledge to draw from to solve standard problems (like a computer)
        - Adaptive: Ability to use that knowledge in novel situations and other domains
    - Shared mental models and overlapping knowledge support performance of procedures in familiar environments (e.g., Salas & Fiore, 2004); expert teams understand roles and the

team task at a level that's sufficient for coordinating actions (e.g., Rentsch & Davenport, 2006)
    - Four levels of task inter-dependence:
        - Pooled: Sum of each person's output is team's output (everyone more or less performs tasks independently, however)
        - Sequential: Member A's output is Member B's input
        - Reciprocal: Member A's output is Member B's input, and vice versa
        - Team: "Team members jointly diagnose situations to anticipate needed actions and coordinate to make decisions and adapt to complete a task" (p. 331)
- Adaptability: Behavior initiated based on recognizing a cue that signals a change in team's behavior should occur
    - Realization by team of an error in execution
    - Realization of error in planning
    - Realization that current situation hasn't been prepared for
- Expertise requires ability to identify (perceptual knowledge) and comprehend (conceptual knowledge) environmental cues
- Training in complex task environments should focus on "critical information-seeking and information processing behaviors…This may be accomplished by systematically exposing the trainee to a variety of scenarios where, through guided practice and feedback, he or she may develop the knowledge structures necessary for rapid and accurate situation assessment" (Salas, Prince, Baker, & Shrestha, 1995, p. 133)
- Perturbations (disruptions in training) improve team coordination in operational contexts
- Stress leads to attention-narrowing that negatively influences perceptual processes and cognitive readiness (Driskel, Salas, & Johnston, 1999). Positive self-talk can reduce the occurrence of negative thoughts that interfere with performance (Tenenbaum et al., 2008), and is used more frequently among skilled athletes than less-skilled athletes (Hardy, Hall, & Hardy, 2004)
- Experts in dynamic environments must be able to transition quickly from pattern recognition to decision making (Klein & Hoffman, 1993), do so through "noise" in the environment, and assess how cues relate to teammates' roles.
- Experts are often able to solve problems without searching much in the problem space because of superior pattern recognition (Salas & Klein, 2001)
- Training should attain cognitive authenticity (cognitive processes stimulated are like those of experts), which means it should include:
    - Accurate types of decisions/judgments
    - Accurate context (physical environment, uncertainty, lack of resources, stressors)
    - Perceptual cues/indicators
    - Background factors available to trainee
- Types of environmental cues:
    - Timeline (critical events that require response from team)
    - Situational (anomalies in environment)
    - Team member (team member does something that indicates a response is required)
- Planning knowledge is used to create expectations, execution knowledge is used to carry out plan

Fletcher, J. D., & Wind, A. P. (2014). The evolving definition of cognitive readiness for military operations. In H. F. O'Neil, R. S. Perez, & E. L. Baker (Eds.), *Teaching and measuring cognitive readiness* (pp. 25-52). Boston, MA: Springer.
C*ited by 3*.

Overview: In this chapter, Fletcher and Wind revisit the construct of *cognitive readiness* previously introduced by Fletcher and his colleague Morrison in 2002 to address a gap in the military's approach to ensuring operational readiness among its personnel. In particular, the *training* element of the readiness approach tends to be reductionistic such that performance to be trained is first reduced down into individual tasks, subtasks, and so forth. When trained and practiced as independent tasks and subtasks, much of the complexity inherent to the operational environment is lost. Cognitive readiness was thus proposed as an additional training element that would focus on "the mental preparation (including skills, knowledge, abilities, motivations, and personal dispositions) and individual needs to establish and sustain competent performance in the complex and unpredictable environment of modern military operations" (Morrison & Fletcher, 2002, pp. 1-3).

<u>Claims Requiring Further Research, Research Gaps, and Research Suggestions</u>:
The following claims the authors make the following controversial claims (and acknowledge that they are so):

- *Cognitive readiness components are relatively content- and context-free*. In contrast to the many authors who conclude that proficiency in complex, unpredictable work domains hinges on a rich and deep knowledge base and that this knowledge base is the source of flexible adaptivity, Fletcher and Wind propose that adaptivity in such a work domain is based in relatively content-and context-free forms of the cognitive functions listed below.
- *Cognitive readiness components must be measurable.* As noted by an advisor to the Red Sox, Bill James, in response to the argument that what is difficult to measure is best to ignore, "If you divide the world into s--- that you know and s---that you don't know, and you study the stuff you know, then you're not going to learn very much" (Reiter [2018]. *Astroball: The new way to win it all.* Crown/Archtype Publishing). The cognitive readiness components listed below each involves multiple complex cognitive processes working together in complex and adaptive ways within a complex, evolving situation. To mark the result as simply "correct" versus "incorrect" or, say, "80 percent correct" would do them serious injustice. It would also likely prove quite challenging given the potential for performers to respond in novel, unanticipated ways based on their particular knowledge base, the changing state of the environment, the different ways to 'read' and respond to the environment, and the various opportunities and projections a given Soldier might reasonably see. An alternative to ignoring aspects of cognitive readiness that are difficult to measure is to work with domain experts who understand the more mysterious and tacit aspects of their work and can recognize and even score their presence, even if only subjectively, and provide qualitative diagnostic feedback. In the meantime, requirements for objective measures can be pursued without creating a hole in Soldiers' training.
- *Cognitive readiness components must be trainable.* The authors consider this claim to be the most controversial of their claims, suggesting that many will consider cognitive readiness components to be inherent abilities on the basis of which job selection should be done.

<u>Findings/Proposed Complex Cognitive Skill:</u>
Elements of cognitive readiness identified in this chapter include:

- Tacit knowledge
- Recognition-primed decision making and associated pattern recognition
- Responding to unexpected problems and opportunities
- Ability to remove ambiguity and recognize patterns in chaotic situations
- Ability to identify and prioritize problems and opportunities as they emerge
- Ability to devise effective responses to emergent problems and opportunities

In contrast with competency-based representations of proficiency, the authors propose the following set of cognitive readiness *components*:

- Situation awareness

- Problem solving
- Metacognition
- Decision-making
- Creativity
- Pattern Recognition (the process; not the patterns themselves)
- Teamwork
- Communication
- Interpersonal Skills
- Resilience
- Critical Thinking

Training strategies the authors advocate include:

- Simulation, games, and other authentic, situated experiences
- Free-play, force-on-force engagements in training and operational exercises

Gerber, M., Wong, B. L. W., & Kodagoda, N. (2016). How Analysts Think: Intuition, Leap of Faith, and Insight. In *Proceedings of the Human Factors and Ergonomics Society 60th Annual Meeting*, 60 (1), 173-177. Washington, DC: SAGE Publications.
Cited by 7

Overview: The three cognitive acts that criminal intelligence analysts use to solve problems are, in order: intuition (recognizing a new situation as similar to a past one), leap of faith (a hypothesis about what this new situation is, knowing the guess might be wrong), and insight (unexpected thoughts that occur when exploring the hypothesis and this new situation from many angles)

Claims Requiring Further Research, Research Gaps, and Research Suggestions

- Computer programs that can facilitate insightful thinking and reasoning
- Did interview participants know they were expected to demonstrate intuition and insight? Hopefully not, because that would make their statements more genuine and less forced (we want to see what intuition and insight naturally happens)
- Participant recall will never be perfect and some of the criminal intelligence analysts might want to appear smarter than they actually are, harder-working than they actually are, etc.

Findings/Proposed Complex Cognitive Skill (the three cognitive acts, in order of execution)

- Intuition
  - Allows an individual to recognize a given situation as similar to one from his or her past experience, enabling a quick response
  - “affectively charged judgments that arise through rapid non-conscious and holistic associations” (Dane & Pratt, 2007, p. 40)
  - When environment is unpredictable (e.g., stock exchange, long-term weather) and too many factors are potentially influencing outcomes, intuition might not lead to correct predictions, but in environments that are more predictable (e.g., firefighters, power plant controllers), intuition can provide quick/accurate decisions (Kahneman & Klein, 2009)
  - Feedback during previous relevant experiences is necessary to learn from them (Hogarth, 2001)
  - If there are no reliable cues, intuition based on simple heuristics can be the best form of decision making (Gigerenzer, 2000)
- “Leap of faith”
  - Necessary in uncertain situations where an individual does not have cues that could help him or her understand a problem or foresee possible consequences (Moellering, 2007)

- Even if initial “leap of faith” understanding of situation is wrong, it enables one to start analyzing and searching for solution
    - Based only on an individual’s experience, not all facts (so decision maker should be aware that his or her solutions are uncertain)
- Insight
    - Finds new solutions when existing patterns do not apply and not enough information is supplied (Sternberg & Davidson, 1996; Klein, 2013)
    - “unexpected shift in the way we understand things” (Klein, 2007), “sudden unexpected thoughts that solve problems” (Hogarth, 2001)
    - Three types
        - Identify inconsistency in gathered data
        - Collecting data that are integrated into a solution
        - Escaping impasse by looking at problem from different perspective
    - Combination of unconscious analysis and deliberate analysis
    - Can only occur after intuition recognizes a relevant old pattern and leap of faith interprets that pattern in context

Gobet, F. (2005). Chunking models of expertise: Implications for education. *Applied Cognitive Psychology*, *19*, 183-204.
Cited by 172.

Overview: Gobet reviews two computational theories of learning that emphasize knowledge-chunking mechanisms, chunking theory and template theory, and derives from them insights for instruction and training.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:
- Gobet notes that chunking theory predicts that skills become less generalizable outside the domain of expertise as expertise level increases and knowledge becomes increasingly specialized. (“This is because the perceptual chunks, which act as the condition part of productions, becomes more selective” [p. 194]).
    - As a result, Gobet suggests it may be useful to “supplement the teaching of specific knowledge with the teaching of metaheuristics that are transferable.”
- Gobet notes that training should emphasize recognition different performance cues and conditions as much as how to perform actions and tasks.
- Gobet proposes 12 educational principles that derive from template theory. Some are clearly linked to research-based evidence, but many are not and require further investigation. These are (p. 193):
    - Teach from the simple to the complex
    - Teach from the known to the unknown
    - The elements to be learnt should be clearly identified
    - Use an ‘improving spiral,’ where you come back to the same concepts and ideas and add increasingly more complex new information
    - Focus on a limited number of types of standard problem situations, and teach the various methods in these positions thoroughly
    - Repetition is necessary. Go over the same material several times, using varying points of view and a wide range of examples
    - Avoid spending too much time on historical and anecdotal details
    - At the beginning, don’t encourage students to carry out their own analysis of well-known problem situations, as they do not possess the key concepts yet
    - Encourage students to find a balance between rote learning and understanding

- Encourage students to keep information in a central filing system or a database
- The ability to look ahead possible moves is made possible by knowledge
  Training this ability per se by exercises aiming at improving short-term memory or visualization (e.g., by playing blindfold chess) is not recommended

Findings/Proposed Complex Cognitive Skill:

- Experts use perceptual cues to be highly selective in searching the problem space, sometimes being able to narrow down to one option right away (Klein, 1998). Perceptual cues are an efficient way for long-term knowledge to be retrieved when it otherwise might remain inert (Whitehead, 1929). However, perceptual cues are often domain-specific and most material does not transfer between domains, especially at high levels of expertise. “Metaheuristics” (e.g., how to learn, how to focus attention on important information, monitoring own learning) could help solve transfer issues.
- Teachers should help learners identify key features and provide feedback. If key features are not identified first for students, then paths to target concepts will be relatively inefficient.
- Chase and Simon (1973): Chess masters perceive board layouts in chunks (groups of pieces that form perceptual and semantic units). Masters have encountered more chunks and can remember larger chunks, and also link those chunks to potential actions. They can also imagine hypothetical board layouts and prepare for them. Revisions to chunking theory:
  - Richman et al. (1995): Retrieval structures enable domain-specific material to be indexed and encoded in long-term memory (original theory relied too much on short-term memory)
  - Template theory (Gobet & Simon, 1998): “CHREST simulates the acquisition of knowledge as the growth of a discrimination network, which develops both as a function of the current state of the system and the input from the environment.” Lateral links connect two nodes of information, while templates are made of a core (encodes fixed information) and slots (encode variable information); templates illustrate “how higher-level structures can be built from chunks and provide mechanisms for the rapid LTM encoding shown by experts.”
- Variation in presented problems is crucial for schemata formation: “presenting a narrow range of problems will hamper the acquisition of a sufficient variety of chunks and links connecting them”
- Individual differences are important factor in novice stages (school often falls under this category)

Goldstone, R. L., & Wilensky, U. (2008). Promoting transfer by grounding complex systems principles. *The Journal of the Learning Sciences*, *17*(4), 465-516.
Cited by 152.

Overview: Goldstone and Wilensky argue that a complex-systems science perspective to complex knowledge and skills instruction can help learners take their focus off basic structural elements of a complex, abstract system and begin to understand the dynamics, interrelationships, and emergence.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- These researchers suggest that the difficulties found in learning complex systems are associated with (1) “cognitive load limitations of computing interactions of large numbers of objects,” (2) “limitations in perception of objects at multiple scales,” and (3) “a lack of micro-level contextual clues” (p. 13).
- “giving people experience with one system embodying a principle can prime their ability to see another system as embodying the same principle. This should be particularly true if the priming is visual, rather than strictly intellectual” (p.36) In other words, teach generalizable knowledge of abstract principles about emergence and other complex-system phenomena.

- *Note*. Work on analogical reasoning (e.g., Gentner, Holyoak, and others) shows that people frequently fail to apply principles across problems or domains.

Findings/Proposed Complex Cognitive Skill:

- An empirical evaluation was not conducted.

Henderson, S., Hoffman, R., Bunch, L., & Bradshaw, J. (2015). *Applying the Principles of Magic and the Concepts of Macrocognition to Counter-Deception in Cyber Operations*. Paper presented at the12th International Meeting on Naturalistic Decision Making, McLean, VA. Retrieved from http://www2.mitre.org/public/ndm/papers/posters/HendersonHoffmanBunchBradshaw040215.pdf *Cited by 1.*

Overview: The authors liken cyber-attacks to magic "ploys" that take advantage of, manipulate, and disrupt the sensemaking processes of the audience or, in the case of cyber-attacks, of the defenders. They present a case study to illustrate the comparison and propose a cyclical model of the macrocognitive processes that play out between attackers and defenders as they attempt to anticipate and manipulate one another's sensemaking processes.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- The authors lay out an initial model of the cycle of cognitive tasks involved in cyber-attack and defense. This model could be evaluated against additional data. It might also be used to ground the identification of skills and associated training support needed by cyber attackers and defenders.

Findings/Proposed Complex Cognitive Skill:

- Cyber defense operations require critical thinking supported by sensemaking. Defenders must:
    - Consider whether suspicious activity could be a decoy as the attacker tries to feed the defender's expectations and confirmation bias about what might be a decoy and what might be real,
    - Try to predict the real trajectory of the attack,
    - Find effective frames (i.e., schemas) for making sense of the information received, even as the attacker may be actively trying to guide them toward an incorrect frame or fragmenting their activity pattern to make it more difficult to discern.
    - Determining the attacker's intent and deciding what actions to therefore take, even as the attacker 'accidentally' shows her hand to mislead or sends cues that could be used to confirm incorrect intents.

Hmelo-Silver, C. E., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *The Journal of the Learning Sciences*, *16*(3), 307-331. *Cited by 264.*

Overview: This study investigated expert-novice differences in knowledge about the human respiratory system and an aquarium ecosystem. A Structure-Behavior-Function (SBF) framework was used for describing and investigating knowledge representations. Expert-novice differences were found in the understanding of causal behaviors and functions; i.e., "the least salient elements of the systems." In addition, experts' mental models tended to be specialized around the focus of their interactions with the system; for one group of experts, this was a focus around local goals; for the other, this was a focus on the global ecosystem.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- "The general instructional pattern followed by teachers and textbooks alike is to treat biology as a collection of objects, definitions, and cycles to be memorized (American Association for the Advancement of Science, n.d.). This instructional methodology promotes a structure-centered approach to understanding and, in turn, may cause students to miss the connectedness that characterizes systems" (p. 327).
- "However, the essence of understanding a system is the dynamic processes of the system rather than the static structures. Function-centered instruction should help students to conceptualize systems as a web of interrelated behaviors that allow structures to accomplish particular functions and should promote more coherent understanding" (p. 327).
- "Organizing learning around deep principles such as SBF should enable students to understand new complex systems they encounter" (p. 327).
- "The tendency of learners to focus on observable structures and simple explanations suggests that the SBF representation may provide a deep principle that is useful for thinking and learning about complex systems" (p. 311)
- How can we teach complex material such that past knowledge and concreteness, both of which aid in knowledge absorption/integration, do not cause uncorrected distortions and misconceptions?

Findings/Proposed Complex Cognitive Skill:

- *Rich, complex knowledge* representation: "Making sense of complex systems requires a representation of concepts and principles that correspond to key phenomena and the relationships across different levels of a system, whether it is micro to macro, or structure to behavior to function" (p. 310).
- *Abstract thinking, Avoidance of cognitive bias traps*: "This is hard because it requires abstract thinking and often conflicts with existing conceptions (Feltovich et al., 1989)" (p. 310).
- "It is understanding the interactions among parts that promotes expertise and true bridging explanations" (Goldstone & Wilensky, 2008, p. 14) and "understanding causal behaviors and functions" (abstract).

Hoffman, R.R., Trent, S., Merritt, D., & Smith, S.J. (in press). Modeling the cognitive work of cyber protection teams. *Cyber Defense Review*.

Overview: The authors conducted a review of literature on cyber defense work followed by interviews with 50 cyber protection teams (CPTs) and used the information to iteratively develop a detailed model of CPT work activities and workflows.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- No claims or gaps stand out in this descriptive work other than the question of which other organizational structures or descriptive labels might be used to represent the results of the authors' cognitive task analysis.

Findings/Proposed Complex Cognitive Skills: A model was produced to represent the results of the literature review and extensive interviews consists. At the highest level of the model are four primary cognitive-work activity categories:

- Planning,
- Monitoring/Collection,
- Sensemaking, and

- Closure. (*Note.* Closure seems more procedural than the other three activities, which seem to involve more complex, cognitive work.)

Within each of the four high-level activities are many sub-tasks and activities. Many of these are procedural tasks that would not, on their surface, be considered complex. Upon evaluation of the detailed version of the model, the following work activities seem related to complex cognitive skill:

- The noticing of potential vulnerabilities or threats
- The continuous evaluation of risks
- Formation of a common operating picture, or situation awareness/assessment by drawing together initial and incoming information
- Sensemaking activities that involve understanding, integrating, and evaluating information (e.g., from on-site forensics and malware analyses, host analysis, and network analysis, which can include terrain and threat characterization).
- The drawing of implications from guidance documents, preliminary advance information, and situation assessments to inform, for example:
  - Plans, both initial and re-planned
  - Strategies e.g., for collecting and monitoring traffic
- Recognizing information gaps so that effective Requests for Information (RIFs) are made.
- Prioritizing objectives, tasks, and activities, both within the plan and in response to changing situation parameters.
- Creation and adjustment of plans, strategies (e.g., monitoring/collection strategies), and priorities in ways that:
  - are responsive to the changing situation
  - are sensitive to objectives and priorities

In summary, critical aspects of this work are the:

- Synthesis of information (i.e., situation assessment),
- Recognition and collection of information needed to build that synthesis,
- Continuous updating of the synthesis, and
- Use of that situation assessment/information synthesis to guide plans, strategies, priorities, and detection of irregularities/threats (perception).

Hutton, R., Ward, P., Gore, J., Turner, P., Hoffman, R., Leggatt, A., & Conway, G. (2017). Developing adaptive expertise: A synthesis of literature and implications for training. In J. Gore & P. Ward (Eds.), *Proceedings of 13th International Conference on Naturalistic Decision Making* (pp. 81-86).

Cited by 1.

Overview: A literature review was conducted to examine research and theory related to the development of adaptive expertise (vs. routine expertise). In addition, 30 stakeholders were consulted via workshops and interviews. A definition of adaptive expertise and six adaptive skill training principles were derived. Training principles were mapped to concrete training interventions.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Should adaptivity be a focus of training, vs critical thinking, analytical rigor, or other cognitive skills?
- How should adaptability be developed? Assessed?
- What are other ways to incorporate the recommended training principles into training initiatives and curriculum?
- The identified training interventions require evaluation

Findings/Proposed Complex Cognitive Skills:

- Well-developed conceptual knowledge structures and exposure to variety are central to adaptive expertise
- Derived definition of adaptive expertise: "*Timely changes in understanding, plans, goals, and methods in response to either an altered situation or updated assessment about the ability to meet new demands, that permit successful efforts to achieve intent*" (p. 83).
- Adaptive skill training principles:
  - Flexibility-focused feedback,
  - concept-case coupling,
  - tough case time compression,
  - tough case proficiency scaling,
  - complexity preservation including an instructional shift away from 'knowledge storage' toward' thinking dynamically', and
  - active reflection.
- The recommended training principles are geared toward developing improved mental models, "habits of mind", and the "sense of typicality required to support anomaly detection and the need to adapt' (p. 85).
- The training principles were mapped to specific training interventions.

Klein, G., Moon, B., & Hoffman, R. R. (2006). Making sense of sensemaking 1: Alternative perspectives. *IEEE Intelligent Systems, 21*(4), 70-73.
Cited by 709.

Overview: This article provides an overview of interpretations of sensemaking from psychology, human centered computing, naturalistic decision making (NDM), and it debunks myths associated with sensemaking. For instance, the myth that "sensemaking is simply connecting dots" overlooks the task to only connect relevant dots with while ignoring others (p.72). Also, "sensemaking follows a waterfall model of how data lead[s] to understanding" is untrue because "sensemaking doesn't always have clear beginning and ending points" (p. 72). It instead is an ongoing process that adapts to new, incoming material.

Findings/Proposed Complex Cognitive Skills:

- Sensemaking involves continuous effort to understand connections in order to anticipate their trajectory and act effectively. In other words, it consists of:
  - Understanding how components interact with each other to form the overall complex system and
  - Developing an evolving hypothesis by ascertaining a theory early and continuously testing it (while maintaining an open mind to the possible need to change the theory).

Klein, G., Moon, B., & Hoffman, R. R. (2006). Making sense of sensemaking 2: A macrocognitive model. *IEEE Intelligent Systems*, *21*(5), 88-92.
Cited by 454.

Overview: This article introduces the construct of a frame to provide a structure to discuss the process of sensemaking. Sensemaking is a continuous effort to understand connections in order to draw a hypothesis and act effectively. The frame represents the created hypothesis which is then tested or questioned by new data. The outcomes of questioning lead to elaborating, reframing, or recreating a hypothesis. This process, coined by the authors, is the *Data/Frame Theory of Sensemaking*.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Additional research to contribute to the evaluation, adaptation, and testing of claims of the Data/Frame Theory

Findings/Proposed Complex Cognitive Skill:

The authors discuss how Data/Frame Theory is used in decision making and describes decision making as consisting of:

- Causal reasoning,
- Questioning hypotheses,
- Receiving feedback and learning from it,
- Designing richer mental models by developing sensemaking skills, and
- Detecting when the active frame is inappropriate.

Sensemaking Skills as represented in the Data/Frame model include:

- Elaborating a frame,
- Questioning a frame,
- Evaluating a frame,
- Comparing alternative frames,
- Reframing a situation, and
- Seeking anchors to generate a useful frame.

Expert-novices sensemaking differences were described and include the following:

- Domain experts are more likely to question data relative to novices because they are, according the authors, more skeptical of data that conflicts with their active/chosen frame.
    - This implies that experts are less susceptible to confirmation bias.
- "Skilled decision makers shift into an active mode of elaborating a competing frame once they detect the possibility (or become worried) that the current frame is potentially inaccurate" (p. 90).
- Novices tend to be less confident in the frame they have chosen for interpreting and responding to a given situation.

Klein, G., Pliske, R., Crandall, B., & Woods, D. D. (2005). Problem detection. *Cognition, Technology & Work, 7*(1), 14-28.
Cited by 151.

Overview: This article compared Cowen's model of the problem recognition process to problem recognition during incidents that occur in natural settings. According to Cowan, problem recognition results with the passing of a threshold in the amount of discrepancies between what is being observed and what is expected. After reviewing a variety of incidents, the authors recommended adaptations to Cowan's model. According to the authors, a discrepancy can only be detected if the person manages their attention appropriately. Specifically, the person must have a flexible, even suspicious, stance where *stance* refers to a person's level of suspicion that something maybe wrong, emotional status, and current alertness. Appropriate attention management additionally depends on domain experience. Experience aids in the development of rich mental models that can be used to differentiate what is normal from what is abnormal, even in terms of subtle signals. The authors give an example of how an experienced nurse was able to recognize a newborn's subtle signals of sickness by, for example, the color of his skin in relation to their body temperature readings, whereas the signal was missed by the inexperienced nurse who was observing the infant. The experienced nurse had enough knowledge of the domain to know something was atypical and her current stance was one of being ready to recognize the subtle cues of a sick infant.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:
The authors only cover two domains and fewer than ten incidents in their study; further research that includes more incidents and in a wider variety of domains would contribute to a more robust analysis and characterization of problem detection.

Findings/Proposed Complex Cognitive Skill:
Both experience and stance contribute to the problem detection process.

- Experience contributes:
    - Development of mental models about how complex systems work which will help a person judge when to trust data and when to seek more information
    - Knowing what is typical and using it as a baseline for detecting anomalies, violations of mental models, and patterns and expectancies
    - Perceiving subtle complexes of signals that may point towards an atypical situation
- Stance involves having:
    - A moderate to high level alertness
    - A level of suspicion that leads to active searching when a person is uncomfortable with the results they receive based on other signals
    - An emotional state that reflects the current level of anxiety and willingness to attend to anxiety-related cues

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.
Cited by 355.

Overview: This article discusses the study of macrocognition and proposes a taxonomy of macrocognitive activities and processes. Macrocognition is proposed as a means for describing cognitive activity performed in natural decision-making settings. Macrocognition is the emergent product of cognitive micro processes that are integrated and adapted to support cognitive work for performance in a particular domain.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Research is needed to evaluate and refine the proposed description and taxonomy of macrocognitive functions and supporting processes. Questions suggested by the macrocognition construct include:
    - How to train for these functions and supported processes for individuals and teams?
    - How to measure acquirement of these functions and supported processes for individuals and teams?

Findings/Proposed Complex Cognitive Skill: The authors propose a framework of macrocognitive functions and supporting processes for teams and individuals.

- *The functions are:*
    - Naturalistic decision making
    - Sensemaking/situation assessment
    - Planning
    - Adaption/replanning
    - Problem detection
    - Coordination
- *The supporting processes are**:***

- Mental simulation and storyboarding
- Maintaining common ground
- Developing mental models
- Managing uncertainty
- Turning leverage points into courses of actions
- Attention management

Klein, G., Snowden, D., & Pin, C. L. (2011). Anticipatory thinking. In K. Mosier & U. Fischer (Eds.) *Informed by knowledge: Expert performance in complex situations* (pp. 235-246). New York, NY: Psychology Press.
Cited by 55.

Overview: This chapter discusses the purpose, features, and barriers to anticipatory thinking. Anticipatory thinking can help detect problems and prepare to act on potential events, including those with low probability. According to the authors, anticipatory thinking is a critical macrocognitive function and is the future-oriented aspect of sensemaking. However, it is different from predicting because it is "gambling with attention to monitor certain kinds (including low probability – high threat) of events and ignore/downplay others" (p. 235). Anticipatory thinking helps a person prepare to act, detect problems and "handle greater uncertainty and ambiguity" (p. 235).

Findings/Proposed Complex Cognitive Skill:

- The authors identify three common forms of anticipatory thinking:
  - Pattern matching
  - Trajectory tracking
  - Convergence
- Anticipatory thinking is a key part of decision making
  - Hypothesized to contribute to the generation of expectancies
  - Enables the decision maker to mentally simulate courses of action and evaluate what problems they might lead to
- Anticipatory thinking is critical to:
  - Team coordination
  - Planning/Replanning
  - Problem detection

Lathrop, S. D., Trent, S., & Hoffman, R. (2016). Human factors research towards cyberspace operations: A practitioner's perspective. In D. Nicholson (Ed.) *Advances in Human Factors in Cybersecurity. Advances in Intelligence Systems and Computing: Vol. 501* (pp. 281-293).
Cited by 3.

Overview: In this article, two cyber operations professionals and a human factors professional collaborate to describe the work of cyber operations, the challenges they face, and the ways cognitive engineering and experimental psychology practices could be used to benefit the current state of the profession.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- A gap the authors identify is developing training and on-the-job support, such as active mentoring, that enables low-experience professionals to perform proficiently in a domain that requires levels of knowledge and skill that would typically take many years to acquire.

Findings/Proposed Complex Cognitive Skills: The authors describe the work of cyber operations (which they distinguish from the work of cyber security) as requiring:

- "Intimate knowledge of system internals to comprehend the state of the system and identify options for configuration and employment…"
- "A deep understanding of the content and format of packets, assembly language functionality, understanding of network protocols"
- Continuous learning to keep pace with clever adversaries

According to the authors, this type of knowledge and flexibility typically requires years of experience; yet in military operations, cyber operations are the responsibility of junior analysts with fewer than two years of experience supervised by generalist officers. Given this organizational configuration, analysts need tools, mentoring, and training that can help them rapidly learn and build their knowledge base.

McNeese, M., Cooke, N. J., D'Amico, A., Endsley, M. R., Gonzalez, C., Roth, E., & Salas, E. (2012, September). Perspectives on the role of cognition in cyber security. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56*(1) 268-271.
Cited by 18.

Overview: This article consists of abstracts written by each of six panelists on the theme of cognition in cyber security.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Panelist Cooke notes that the cyber defense field lacks team training although evidence suggests it is badly needed.

Findings/Proposed Complex Cognitive Skill: The paper proposes that cyber defense involves:

- Generative learning
- Deep levels of thinking and perception, i.e.:
    - Situation assessment
    - Sense making,
    - Information seeking,
    - Decision making, and
    - Visualization
- Distributed collaboration to execute coordination, communication, and joint action
- Resistance to deception, spoofing and a false sense of security

Mumford, M. D., Friedrich, T. L., Caughron, J. J., & Byrne, C. L. (2007). Leader cognition in real-world settings: How do leaders think about crises? *The Leadership Quarterly, 18*(6), 515-543.
Cited by 204.

Overview: The authors apply research about expertise acquisition and knowledge representation to the skills involved in leadership response to crises and change events. From this knowledge base, they generate hypotheses about how leaders make decisions, the errors they may make, and the factors contributing to errors. They emphasize the role of experience in the form of past cases, the limits working memory/cognition place on the richness and number of past cases that can be used at one time, and the use of workload/information load strategies that may lead to errors.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- The authors describe their recent research finding that while generating creative solutions, people can work with only a few cases at once due to the complexity of case-based knowledge.
    - Research questions: How complex? How many cases? Effect of expertise?
- The authors identify 19 propositions/hypotheses that could be studied. These include the effects of high cognitive load on the use of experiential (case-based) knowledge, simplification strategies, such as stereotypes and other biases that can lead to errors, and the potential for strategic metacognitive knowledge to be used to avoid error traps (e.g., related to the use of simplification strategies).

Findings/Proposed Complex Cognitive Skill:

- No findings. This work is a literature review and discussion.

Paul, C. L., & Whitley, K. (2013). A taxonomy of cyber awareness questions for the user-centered design of cyber situation awareness. *International Conference on Human Aspects of Information Security, Privacy, and Trust* (pp. 145-154). Berlin: Springer.
Cited by 22.

Overview: Based on interviews with six analysts and 25 hours of observation, the researchers derived a list of 44 questions analysts ask themselves in order to establish and maintain awareness of new and ongoing network events. They used a card-sorting exercise, performed by 12 analysts, to evaluate and organize the questions. Co-occurrence, cluster, and cluster content analyses were performed to produce a *Taxonomy of Cyber Awareness Questions for Cyber Situation Awareness*.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Additional work is required to further evaluate the taxonomy. Although the 44 interview questions were derived from studying and observing six cyber security experts prior to the card sorting activity, the authors do not discuss their particular backgrounds relative to the areas covered by the taxonomy. Therefore, some of the questions asked to be sorted may not cover an area of concern for each analyst.
- This study only focused on one job type in cyber security and to the analysis and taxonomy should be extended.

Findings/Proposed Complex Cognitive Skill:

The taxonomy consists of 39 questions grouped into:

- Three categories of *Event Detection* questions:
    - *Network Baseline*
    - *Change Detection*
    - *Network Activity*
- Three categories of *Event Orientation* questions:
    - *Event Identification*
    - *Mission Impact*
    - *Damage Assessment*

Ratwani, K.L., Dean, C.R., Knott, C., Diedrich, F., Flanagan, S., Walker, K., & Tucker, J.S. (2016). *Measuring Leader Attributes in the Army Reconnaissance Course* (ARI Research Report 1993). Fort Belvoir, VA: U.S. Army Research Institute for the Behavioral and Social Sciences. (DTIC No. AD1003296)
Cited by 2.

Overview: Outlines the development of a prototype software that measures and assesses soldier competencies (leadership especially), describes findings suggesting that soldiers find this software useful (mostly an administrative and book-keeping document)

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Enhancements are needed for the tool to be functional within the Army Reconnaissance Course
- Assessment of leadership

Findings/Proposed Complex Cognitive Skill

- Training must occur outside of the classroom and shift to "a blended, more individualized model that incorporates the three pillars of leader development: institutional instruction, self-development, and operational experience (U.S. Department of the Army, 2013)
- Army Reconnaissance Course – Attributes of leaders
    - Accountability: Takes responsibility for own and team's actions and consequences
    - Adaptability: Manages changing requirements for balancing unit recon, surveillance, and security with mission accomplishment
    - Anticipation: Foresees future requirements and conditions
    - Confidence: Believes in own and team's ability to handle tactical situations
    - Initiative: Thinks and acts without being urged
    - Problem solving: Solves problems by applying deliberate thought
    - Risk management: Assess the situation against the mission and makes a decision – effectively balances mission requirements and risk
- Leadership is very subjective to evaluate (and generally inconsistent) and if instructors rotate as they often do, assessments might be messy

Ross, K. G., Phillips, J. K., & Rivera, I. D. (2014). *Small Unit Decision Making (SUDM) Assessment Battery Final Report: Option III*. Arlington, VA: Office of Naval Research. (DTIC No. ADA614120)
Cited by 1.

Overview: This report describes the development and validation of a battery of test instruments that are predictive of the decision-making proficiency of infantry small-unit leaders. Instruments consisting of behaviorally anchored rating scales were developed to measure skills and attributes that were identified through a series of workshops and surveys as enabling proficiency small-unit leader decision making. From the results of those workshops and surveys, five competencies and ten cognitive and relational skills were selected for assessment-battery development. Instrument analyses support their reliability, construct validity, and predictive validity. Predictive validity was assessed by comparing instrument scores to the results the Decision Requirements Interview, a performance instrument created by the same project team.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- In contrast to Fletcher and Wind's (2014) characterization of cognitive readiness components as context- and content-free, these authors propose they require adaptation to a particular domain context and depend on domain-specific knowledge and experience.
- In contrast to Fletcher and Wind's cognitive readiness components, these authors treat cognitive readiness components as all interrelated and supportive of decision making, treating that particular component of Fletcher and Wind's definition in a more holistic and multi-dimensional way. The authors claim that doing so "allows a richer, clearer picture of this critical performance to emerge, avoids a limiting approach to assessment, and allows us to better address the original, holistic definition of cognitive readiness" (p. 3).

Findings/Proposed Complex Cognitive Skill:
Ross and her colleagues developed assessment instruments that target the following small-unit leader *decision-making readiness* constructs:

- Problem solving
- Metacognition
- Attention control
- Adaptability
- Sensemaking
- Perspective taking
- Analytical reasoning
- Anomaly detection
- Resilience
- Change detection
- Situational assessment
- Cognitive flexibility
- Ambiguity tolerance
- Self-regulation
- Self-awareness
- Decision making

Schatz, S., Bartlett, K., Burley, N., Dixon, D., Knarr, K., & Gannon, K. (2012). *Making good instructors great: USMC cognitive readiness and instructor professionalization initiatives* (Technical Report No. 12185). Quantico, VA: Marine Corps Training and Education Command. *Cited by 2.*

Overview: The authors discuss a need to enhance cognitive readiness for small unit, enlisted ground personnel in the US Armed Forces because their duties require them to operate in a fast-paced, decentralized, ambiguous environment. Two complementary initiatives were created because there is no official list of cognitive readiness skills or a way to train instructors how to teach those skills. First, the Small Unit Decision Making (SUDM) initiative identified cognitive competencies associated with cognitive readiness. The SUDM organizers then developed approaches for the small unit leaders to foster these competencies in their subordinates. Second, the Instructor Professionalization initiative improved upon the USMC instructor development and evaluation process for training cognitive readiness.

Findings/Proposed Complex Cognitive Skills:
The SUDM initiative, consisting of a review current research and a series of workshops with academic advisors, enlisted personnel, and senior mentors, focused on intuitive decision-making and complex problem-solving skills to develop small-unit leader cognitive readiness competencies. The following competencies were identified (p. 2):

- *Adaptability:* Consistent willingness and ability to alter attitudes, thoughts, and behaviors to appropriately respond to actual or anticipated change in the environment.
- *Attentional Control:* Ability to direct and sustain attention on a deliberately chosen target, tolerate sustained attention even when unpleasant, and maintain awareness of own attention.
- *Metacognition*: Thinking about your own thinking; using cognitive strategies to monitor/self-regulate learning and other mental process.
- *Problem Solving:* Understanding the problem space, generating possible solutions, and applying complex strategies to achieve (or move toward achieving) a specific goal.

- *Sensemaking:* Understanding connections (e.g., among people, places, and events) in order to anticipate their trajectories, estimate the overall situation, and act effectively.

During the SUDM initiative, participants noted the importance of expert knowledge because it "build[s] robust mental libraries of diverse experiences" (p. 2), which aids in effective decision making, and stressed the need for developing "great" instructors to enhance the learning process of the five identified competencies.

Framework for Making Good Instructors Great

The competencies and approaches defined in the first initiative were used to develop an instructor training program, "Making Good Instructors Great." As part of developing the instructor training program, the authors identified four attributes that are essential for an instructor to transform into a "great" instructor:

- *Leadership: S*ets big goals with measurable standards, encourages and motivates students, uses mastery learning.
- *Communication:* Actively engages student in a dialog, presents content in a clear and compelling way, fluidly adapts communication style in different settings.
- *Expert Technique:* Develop a "bag of [instructional] tricks" that can be used to provide alternative approaches to engage students. The authors describe various implementation strategies including specific scenario-based learning methods, instructional tactics, and assessment techniques.
    - *Scenario-Based Learning Methods:* Approaches to use in addition to current scenario-based training methods.
    - *Instructional Tactics:* Supplements to enhance military instruction. These tactics are categorized by type of learning environment, such as direct, indirect, interactive, independent, and experimental, and by student proficiency level and amount of time. This will aid the instructor to have vast array of choices based on the needs to the students, time, and training environment.
    - *Assessment Techniques:* Various assessments depending on current stage of training, such as checking progress or establishing a based line. These techniques do not explicitly assess the cognitive competencies, but instead attempt to gauge growth in intuitive decision making and problem solving.
- *Character:* The instructor is a role-model for students and seeks self-improvement.

The training program was beta tested and the initial reviews of the course were positive. However, a formal evaluation of the cognitive competencies described in the first initiative are in fact taught or enhanced through the training program has yet to be completed.

Schwartz, D. L., Brophy, S., Lin, X., & Bransford, J. D. (1999). Software for managing complex learning: Examples from an educational psychology course. *Educational Technology Research and Development*, *47*(2), 39-59.
Cited by 190.

Overview: STAR.Legacy is a flexibly adaptive software shell that guides students' attempts to do complex problem-based learning. It integrates four major concepts: Pre-existing student KSAs, knowledge that is organized around important core concepts, visibility of students' thinking, and community-centered environments that encourage collaboration. The stages (in this general order, but can be adapted): Look Ahead, Generate Ideas, Multiple Perspectives, Research and Revise, Test Your Mettle, Go Public

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Students who compare their best solutions at the end to their own starting solutions report learning more than those who did not do this comparison activity – do those students actually learn more or just *feel* like they learned more?
- "An important research question is how to support less sophisticated students so they can effectively learn to self-assess (for an approach that uses contrasting cases, see Lin & Bielaczyc, 1998)" (p. 50)

<u>Findings/Proposed Complex Cognitive Skill:</u>

- Homework assignments can produce what seems like learning, but students often fail to use their learned knowledge when placed into a new setting ("inert knowledge"; Whitehead, 1929), a common problem with "traditional" instructional methods.
- Proposed solutions to "inert knowledge" have included problem-based, case-based, and project-based learning methods. Risks include:
  - Mistaking engagement with learning
  - Assuming that constructivist methods require elimination of traditional activities such as readings and lectures; actually, novices just need to be properly prepared (i.e., be able to sufficiently differentiate their knowledge) to appreciate insights of readings and lectures
- To achieve a complex learning goal, it might be necessary to explicitly map out how each learning activity contributes to the larger goal (SMART maps showed how activities sequenced together to help complete final project; Vye et al., 1998)
- Goal-setting is important, but list of goals must be coherent (not vague and unrelated to each other). Benefits to previewing the domain and setting learning goals:
  - Help students contextualize new information within prior knowledge and communities of practice
  - Help students envision their destination in a domain of knowledge
  - Facilitates classroom discourse through shared domain model
  - Identifies what students need to learn more about and helps teachers anticipate students' pre-existing knowledge/attitudes
  - Provides a benchmark for reflection
- Requiring students to generate ideas first (before finding out canonical information) forces them to make their thinking explicit and creates opportunities for easy comparison to canonical information later (students can't just say something is "common sense" when it was shown that they thought otherwise), hopefully resulting in useful revising of their ideas (Bransford et al., 1989)
- Multiple perspectives are important for increasing flexibility in future problem solving (Spiro & Jehng, 1990)
- Formative assessments, as opposed to post-tests, help students gauge their understanding, along with idea revision opportunities afterward and getting the chance to compare their new ideas with their original ideas (Barron et al., 1995)
- Presenting best solutions to others accomplishes two things:
  - High-stakes presentation motivates students to do well
  - Other students and teachers can appreciate high-quality understanding
- The chance to appreciate one's own growth in a complex area is important, especially for lower-achieving students

Staller, M. S., & Zaiser, B. (2015). Developing problem solvers: New perspectives on pedagogical practices in police use of force training. *Journal of Law Enforcement, 4*(3), 1-15.
Cited by 16.

<u>Overview:</u> The authors describe use-of-force training practices that are better suited to procedural and physical skills, versus for using knowledge and decision making to responds adaptively in complex, challenging situations. More specifically, they discuss the need to move toward the naturalistic decision making (NDM) process for use-of-force training for police, rather than the current training paradigm, which seeks to produce automaticity in techniques such as self-defense moves and the use of control and restraint. The authors claim that current training practices have not proved effective for several reasons including that the training does not actually reflect reality (i.e. "The attackers don't stand around and attack you stupidly; they charge at you" (p.4)), behavioral training of making actions become automatic can cause "he or she [to perform] well one day, and disastrously the next", and the type of environment that officer must react in is not predictable and time sensitive (p.8). The authors suggest that adopting NDM-based training would better prepare officers for reacting in uncertain and time-sensitive situations. This training would focus more on teaching cognitive skills that support assessment and reacting in dynamic, complex situations rather than on developing automaticity within specific, prescribed examples. The use of NDM-based training would allow officers to acquire "the process of [a] solution" rather than the specific steps of a problem (p. 10).

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- The authors propose a pedagogical strategy that is better aligned with the challenges of use-of-force situations. However, the details of implementing the strategy have yet to be specified and the effectiveness of the strategy and its implementation has yet to be evaluated in this domain.

Findings/Proposed Complex Cognitive Skill:

- The article reiterates the Fautua and Schatz (2012) characterization of cognitive readiness as depending on: "…successful pattern recognition, creative adaptability, and intuitive decision making" (p.6).

Szpunar, K. K., Spreng, R. N., & Schacter, D. L. (2014). A taxonomy of prospection: Introducing an organizational framework for future-oriented cognition. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 18414-18421.
Cited by 174

Overview: Taxonomy of prospective cognition

	SIMULATION	PREDICTION	INTENTION	PLANNING
EPISODIC	Construction of a mental representation of a specific autobiographical future event.	Estimation of the likelihood of and/or one's reaction to a specific autobiographical future event.	Setting a goal in relation to a specific autobiographical future event.	Organization of steps needed to arrive at a specific autobiographical future outcome.
	Construction of a mental representation of a non-specific autobiographical state.	Estimation of the likelihood of and/or one's reaction to a non-specific future autobiographical state.	Setting a non-specific autobiographical future goal.	Organization of steps needed for some non-specific autobiographical state to arise in the future.
SEMANTIC	Construction of a mental representation of a general or abstract state of the world.	Estimation of the likelihood of and/or one's reaction to a general or abstract future state of the world.	Setting a general or abstract goal, such as the goal of an organization.	Organization of steps needed for some general or abstract state of the world to arise in the future.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Future research programs should consider both "connections and distinctions among the modes of future thinking"
- "…whether episodic and semantic forms of simulation, prediction, intention, and planning represent dissociable phenomena or nominal distinctions regarding the content on which these various modes of prospective cognition operate remains to be adjudicated in the literature" (p. 18415)
- "…recent studies have shown that people are able to generate more detailed simulations of the future when they are trained to report those details in the context of a cognitive interview about a recent experience (42). Whether specificity inductions could be used to enhance predictive accuracy awaits future research" (p. 18417)
- "are people who are good at predicting general states of the world [semantic] that may arise in the future also good at predicting the likelihood of occurrence of specific autobiographical events [episodic]?" (p. 18417)
- "…no study has directly compared episodic and semantic planning deficits in frontal lobe patients, and therefore, more work is needed to understand the extent to which these forms of planning are supported by similar and different mechanisms." (p. 18419)
- "…relatively little is currently known about the extent to which the perceived likelihood of the occurrence of a future event might influence the formation and retention of intentions or the quality of plans." (p. 18419)
- "Development of research programs that consider the role of these various modes of future thinking could enhance our understanding of the ability of individuals afflicted with various mood and anxiety disorders to engage in adaptive behavior (e.g., how well are individuals with depression or anxiety able to predict their reactions to future events?; how well are they able to formulate episodic or semantic plans for the future?)." (p. 18419)

Findings/Proposed Complex Cognitive Skill:

- Four modes of future thinking, not necessarily orthogonal to each other (given example: Monika is possibly getting promoted, boss asks her to play tennis over weekend):
  - Simulation (detailed mental representation of future)
    - Episodic simulation (specific): Having discussion about company is likely to take place (mental representation of specific future autobiographical event)
    - Semantic simulation (general): She thinks about the future direction of this company (mental representation of abstract state of world)
    - Episodic memory and episodic simulation engage similar parts of brain
    - Simulation could be directed at past (e.g., how could X have turned out differently)
    - Semantic and episodic are dissociable to some extent: Episodic amnesic patient can't think about what he wants to do in future, but can think about what problems world might face in future (e.g., global warming)
  - Prediction (likelihood of and/or one's reaction to particular future outcome)
    - Episodic prediction: Will the meeting go well, and how will the most likely outcome make her feel (likelihood of and/or one's reaction to a specific future autobiographical event)
    - Semantic prediction: The future of the company will be best served by merging with another company (likelihood of and/or one's reaction to a general/abstract future state of the world)
    - People are generally limited in ability to predict how they will emotionally react to future events (tend to overlook seemingly minor details that end up being important; e.g., predict that you'll be happy as a parent, but overlook the pain of changing diapers)
    - Repeatedly simulating a particular event can increase judgments of perceived likelihood
    - Expectation of positive future outcomes is linked to successful attainment of significant personal milestones, but passive fantasizing impedes that success
  - Intention (mental act of setting goal)
    - Episodic intention: Setting a goal in relation to a specific autobiographical future event (Monika sets goal of buying new sneakers before playing tennis with boss)
    - Semantic intention: Setting general or abstract goal (Monika contemplates the goals of her company over the coming year)
    - Prospective memory example: I need to pick up bread on the way home from work tomorrow
    - Explicitly stating when and where an intention will be carried out increases prospective memory performance
    - Intentions can be both episodic and semantic (e.g., Monika formed intention to pursue career in business)
  - Planning (organizing steps to achieving goal state)
    - Episodic planning: Identifying/organizing steps needed to arrive at specific autobiographical event/outcome (plans the steps to prepare for this meeting)
    - Semantic planning: Identifying/organizing steps needed to arrive at general/abstract state of world (tells boss the required steps to merge with another company)
- Episodic and semantic forms of future thinking can interact
- Mental contrasting (comparing current self with future desired self) is not future-oriented per se, but can stir motivation for future goals
- "…intentions to make a motor movement may be encoded I the brain up to 10s before those intentions enter conscious awareness. The extent to which motor intentions contribute to higher-level or conceptual thoughts about the future awaits additional investigation.

Clearly, however, prospective cognition must inform immediate motor behavior at some junction to organize immediate behavior and accomplish many of the future-oriented thoughts considered" (p. 18420)

U.S. Department of the Army (2017). *The U.S. Army Learning Concept for Training and Education* (TRADOC Pamphlet 525-8-2). Fort Eustis, VA: U.S. Department of the Army, Training and Doctrine Command.

<u>Overview</u>: This document presents an Army vision for supporting career-long learning in order to develop Soldiers who come together as agile, adaptive, and innovative teams. The vision emphasizes the need for an organizational learning culture and mindset, decentralization of learning, and a range of learner-centric, self-paced learning opportunities. It proposes a learning environment model and calls for it to incorporate the learning science, integrated technology solutions that facilitate learning, and investments in human capital such as mentors and teachers.

- Core competencies:
    - Adaptability (adjust attitudes, emotions, neurophysiology, and actions to detected change)
    - Sensemaking (estimate situations in given operational environments)
    - Problem-solving (evaluate the adequacy of generated options and/or choices)
    - Metacognition (using strategies to monitor/self-regulate learning and cognition)
    - Attention control (deploy sustain, targeted attention on a chosen target)
- One of their goals is to blend educational (general/abstract) goals into training programs (those that are usually more focused on specific tasks, might be more procedural and/or psychomotor)

<u>Claims Requiring Further Research, Research Gaps, and Research Suggestions</u>:

- What factors consistently differentiate well-performing units from mediocre units?
- Marines need to be trained to learn while on the job (instead of just doing the job), otherwise they might actually regress in some cases
- Balancing the fact that Marines often must obey orders without question and encouraging them to develop critical thinking
- Small-unit leaders have decision-making responsibilities during operations, but often do not when they return to home base
- The vision expressed in this document requires a great deal of research. For example, it calls for research into:
    - how to mentor effectively and
    - how to design a learning management system that can handle the complexity of all the training a Soldier might potentially experience and that can make reasonable recommendations based on the large variety of scores that could be attained over the course of a career's worth of those experiences.
- A gap is determining how to ensure the relevance of classroom and similar educational experiences with on-the-job and operational experiences.
- The document calls for competencies to be broken down into supporting knowledge, skills, abilities, behaviors, and experiences, "which may be nested into multiple subordinate levels" (p.20). At what point does decomposition and decontextualization start to interfere with the development of holistic, integrated, and fluently used knowledge and skill?
- The document suggests that credit should be given for various operational and practice experiences as a means of tracking readiness on a competency-by-competency basis. How much credit should be given for various types of experiences? When a subtask is performed in one context, can it be given credit for its performance as part of other tasks?

Findings/Proposed Complex Cognitive Skills: The document proposes a vision for U.S. Army training that employs integrated training and education resources within a career-long learning culture to meet the objectives of:

- Strengthening critical and creative thinking,
- Developing strategic thinkers,
- Encouraging technical proficiency, and
- Building cohesive combined arms teams.

It also describes training practices, including:

- Mastery learning prepares all students to the same level with required time and type of activities varying; traditional instruction gives all learners the same amount of time and activities with learning outcomes varying
- Just-in-time training focuses on particular skills and procedures;
- Deliberate practice…
  - focuses on tacit knowledge and intuitive expertise associated with extensive job experience
  - requires accurate and immediate feedback, opportunities for reflection, and chances to repeat tasks until mastery is achieved
  - can be done on the job once foundational skills have been established; that way, the learner can properly "file" the experience into the proper repository of experiences

U.S. Marine Corps Training and Education Command. (2011). *U.S. Marine Corps Small Unit Decision Making: January 2011 Workshop Final Report*. Quantico, VA: Author.
Cited by 4.

Overview: This report describes a workshop conducted with 99 decision making researchers and military leadership experts. The participants were asked to evaluate five core competencies identified during workshop preparations, break them down into subskills, and recommend training and education requirements. The five core competencies were: *adaptability, sensemaking, problem solving, metacognition, and attention control*. Conclusions center around establishing policy and infrastructure to support small unit decision making training. With respect to training and education, experience-based strategies were emphasized, including mentoring/coaching, exposure to challenges and deliberate practice to master them, and the deliberate framing of experience, e.g., by deliberately attempting to anticipate, to facilitate the acquisition of useful tacit knowledge.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Teaching experts how to mentor and coach would be an important contribution to developing small unit decision making expertise (teach "small unit leaders how to guide and facilitate a discussion, explain their decision-making processes and rationales to their units, and help their personnel get the most out of deliberate performance and practice opportunities" [p. 20]).
- How to teach a balance between the discipline required of warfighters who are often expected to follow orders without question with the need to perform flexibly and resourcefully at other times?
- What strategies do military units already use, developed natively or in-house so to speak, to develop complex cognitive skill and what can we learn from them?
- How effective are mindfulness exercises at developing warfighter attentional control and awareness?

Findings/Proposed Complex Cognitive Skills: The breakdown of the five core competencies is presented below (from p. 27; note that the supporting skills are all relevant to each competency):

COMPETENCY	INSTRUCTIONAL GOALS	COGNITIVE AND RELATIONAL SKILLS
Sensemaking	Assess operational environments (estimate the situation).	After Action Review Skills Ambiguity Tolerance Analytical Reasoning/Judgment Anomaly Detection Change Detection Coaching Skills Cognitive Flexibility Contrast Sensitivity Counseling Skills Emotional Acuity/Perception Facilitation Skills Mental Imagery Mental Simulation Mentoring Skills Organizational Skill Pattern Matching Pattern Recognition Perspective Taking (C3) Resilience Self-awareness Self-monitoring Self-reflection Sensory Acuity/Perception Situational Assessment Spatial Cognition Vigilance
Problem Solving	Evaluate the adequacy of generated options and /or choices.	
Adaptability	Detect change and adjust attitudes, emotions, neurophysiology and actions.	
Metacognition	Use strategies to monitor/self-regulate learning and cognition.	
Attentional Control	Deploy sustain, targeted attention on a chosen target	

In addition, participants recommended a number of experience-centered training interventions which are reported in a report annex. They include active listening, critical incident critiques, critical thinking/planning exercises, cross training, crystal ball exercises, decision making exercises accompanied by coaching on biases, guided discussions in conjunction with "garden path" scenarios (which lead a participant down one particular path and then introducing conflicting evidence), and more.

Van Merrienboer, J. J., Kester, L., & Paas, F. (2006). Teaching complex rather than simple tasks: Balancing intrinsic and germane load to enhance transfer of learning. *Applied Cognitive Psychology, 20*(3), 343-352.
Cited by 252.

Overview: The authors propose a variant of their cognitive-load management approach for complex task learning that acknowledges the importance of task variability and diminishing guidance and feedback while taking into account the already-high cognitive load that comes with complexity.

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- Complex task learning should benefit from exposure to versions of the material to be learned that begin with low element interactivity that increases (as expertise increases) while simultaneously introducing germane load in the form of practice variability (from Day 1) and diminishing feedback and guidance.
    - Is an approach that simplifies task dynamics and variable interactions prone to the introduction of misconceptions?
- More research is needed to evaluate the "assumed interaction" between intrinsic-load reducing methods and germane-load inducing methods.
- More research is needed that evaluates the acquisition of highly complex real-life tasks performed in ecologically valid settings. "Particular instructional methods such as variability might then have unexpected effects, for instance because it is difficult for learners to distinguish between the surface and structural features of such tasks" (p. 351)
- Research is needed to improve the measurement of cognitive load, including intrinsic and germane cognitive load elements.
- What other methods might be used to improve the manageability of learning a complex task? How does van Merrienboer's approach compare to an approach that incorporates expert guidance?

Findings/Proposed Complex Cognitive Skill:

- No findings. This work is a literature review to produce recommendations and hypotheses.

Wulfeck, W. H., Wetzel-Smith, S. K., & Dickieson, J. L. (2004). Interactive Multisensor Analysis Training. Paper presented at the *RTO HFM Symposium on "Advanced Technologies for Military Training*. Genoa, Italy: Space and Naval Warfare Systems Center.
Cited by 4.

Overview: IMAT is a performance support system that helps students learn technical concepts about advanced sensor systems. The system aids in visualizing interactive relationships between threat, environment, and sensor systems, and provides a virtual laboratory where those relationships can be explored (largely through "what if" and case-based simulations)

Claims Requiring Further Research, Research Gaps, and Research Suggestions:

- "We have found these discrepancies between introductory and advanced learning often result in situations where the groundwork set down in introductory learning actually *interferes* with successful advanced learning" (p. 8) [probably depends on what kinds of introductory information is provided]
- "proponents of cognitive task analysis have not yet had much success at developing their methods so that they can be routinely applied in complex warfighting tasks, and in some cases this approach has led to overly narrow characterizations of Navy training requirements" (p. 8)
- Need more data on whether the IMAT approach improves performance in actual military operations, not just simulation exercises or post-test measures (as described in this paper). Of course, actual operations are not controlled experiments and therefore definitive conclusions will be difficult to draw, but the goal should be to observe improvements in that area, if possible.

Findings/Proposed Complex Cognitive Skill:

- Criteria for tasks to be considered cognitively complex
    - Abstract (vs. concrete): Difficult to physically observe, cause/effect not easily observed
    - Multi-variate (vs. univariate): Multiple causes for any given outcome
    - Interactive (vs. separable/additive): Underlying causes interact, so effect of one variable might change depending on status of another variable
    - Continuous (vs. discrete): Infinite possible values for variables

- Non-linear (vs. linear): Relationship between underlying dimension and outcome could be exponential, logarithmic, etc.
- Dynamic (vs. static): Relationships between variables change over time
- Simultaneous (vs. sequential): Outcomes change as underlying variables change, not in a sequence
- Conditional (vs. universal): Relationships between variables depend on context and there might be exceptions to rules
- Uncertain (vs. certain): Variable values might have to be estimated or extrapolated/interpolated
- Ambiguous (vs. unique): A given combination of circumstances can result in multiple outcomes, or given outcome can be result of many combinations of circumstances

- Before the advent of IMAT, acoustic operators did not learn oceanography and sound physics in the context of submarine operating environments, mission-dependent characteristics, and frequency-based information resulting from sensor system design. They knew a lot of information in a vacuum but were not as able to implement it in "messy" real-world situations where context determines a lot.
- Task-oriented instruction is more effective than topic-oriented instruction in learning, retention, and performance (Semb & Ellis, 1994)
- Pictures/graphics help if directly related to text (Levie & Lentz, 1982)
- Elaborated explanations about how/why system, events, and phenomena are like they are facilitate learning and retention (Mayer, 1989)
- For complex tasks, instructional sequencing can make a large difference in learning (Czech et al., 1998)

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