A Complex Cognitive Skills Acquisition Framework

Kelly J. NEVILLE[a], Dar-Wei CHEN[a], Sean NORMAND[b], Lauren MASSEY[a], Tyree S. COWELL[a], Gregory A. BURBELO[b], Paul N. BLANKENBECKLER[b], *and* Elizabeth UHL[c]

[a] Soar Technology, Inc.
[b]Northrop Grumman
[c]Army Research Institute

ABSTRACT

Training methods and curricula designed for complex cognitive work are often at odds with research on how complex cognitive skills are acquired. To address this problem, we developed a framework that represents research on advanced proficiency and expertise acquisition in complex cognitive work. The framework, called the Complex Cognitive Skills Acquisition Framework (CCSAF), is the product of an iterative design process based on a literature review. It depicts at a high level the acquisition of complex cognitive skill by individuals and teams through co-evolutionary, adaptive, and integrative processes. It is intended to help decision makers, training practitioners, and instructional designers support advanced proficiency and expertise acquisition in complex cognitive work. The framework may also support the research community as a visualization tool that fosters insights, reveals research questions, and summarizes the state of relevant research. We present an overview of the initial version of the CCSAF in this paper.

INTRODUCTION

Research conducted over the past few decades has significantly advanced our understanding of expertise and proficiency acquisition in complex cognitive work. Despite this progress, little has changed in the way most organizations conduct training, even as work becomes more cognitive and increasingly complex. Many organizations continue to use initial, upfront training, typically followed by periodic refresher training. Often, individuals must rely on self-development initiative to progress in proficiency and expertise. Some will chance upon a strong mentor, and some will even have the fortune of working in an organization that attends to and has developed effective support for the long-term process of expertise development (Neville, Tenison, & Cowell, 2019). Many, however, will not.

The authors are aware of initiatives in certain complex work domains to move away from the upfront one-and-done training model. These include initiatives in the U.S. Navy and petrochemical industry to break curricula into sections interspersed across a person's career. We have also witnessed a case of air traffic control instructors replacing predominantly classroom instruction with a *flipped classroom* model and simulation scenarios (Wiltshire, Neville, & Lauth, 2014). Such improvement efforts might become more common and effective if training decision makers and practitioners were knowledgeable about relevant research on, for example, expertise and its acquisition (e.g., Gobet, 2015; Hoffman et al., 2013), macrocognition and its assessment (e.g., Klein, 2010), and team cognition and its development (e.g., Fiore, Ross, & Jentsch, 2012).

Proficiency acquisition in complex cognitive work can benefit from additional research as well as efforts that facilitate the translation of research into practice. The U.S. Army Research Institute (ARI) proposed the development of a framework to represent and foster research on the acquisition and assessment of complex cognitive skills. The *Complex Cognitive Skills Acquisition Framework* (CCSAF) has potential to be of value to both the research community and training professionals. For the research community, the CCSAF highlights gaps in the current literature and concepts that require further exploration. For practitioners, the CCSAF serves as a visual meta-analysis, summarizing concepts necessary to the development of advanced levels of proficiency in complex cognitive work domains. In this paper, we present an overview of the first version of the CCSAF.

METHODS

Four researchers with psychology or psychology-related degrees (experimental, engineering, and human factors psychology, and cognitive science) conducted a literature review, team brainstorming sessions, and cyclical reviews with three external team members knowledgeable in Army training doctrine and practices. The following objectives guided the framework's development:

- Support research on the acquisition and assessment of Soldiers' complex cognitive skills and

Information for lead author: Kelly Neville, PhD, Research Scientist, Soar Technology, Inc., 12124 High Tech Ave, Orlando, FL 32817; Telephone: 407-602-6123; Email: kelly.neville@soartech.com.

- Support a range of different research approaches and perspectives; for example, approaches and perspectives of basic, applied, experimental, and naturalistic bodies of work.

Literature Review

Forty documents were reviewed and summarized. Thirty-seven were peer-reviewed journal and conference proceedings articles that discuss cognitive work in complex, challenging work domains. Three were government documents consisting of a workshop report, Army publication on its training and education vision, and task force report on training needs in cyber operations. Document search terms included *complex cognitive skill acquisition, macrocognition, complex cognitive work, cognitive readiness, complex cognitive training, complex cognitive assessment,* and *expert proficiency acquisition.*

Team members reviewed the articles to identify elements of cognition (e.g., knowledge, skills, strategies, expert-novice differences, and competencies) characterized as relevant to proficient performance in complex cognitive work. When references to and descriptions of cognitive elements were found, those excerpts were extracted from the document and moved to a spreadsheet. Two team members independently coded 139 excerpted descriptions of and references to cognitive processes, cognitive capabilities, and other 'cognitive elements'. Coding themes were identified by reviewing the excerpts to identify a starting set of themes. 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 and after each increment met to discuss and reconcile coding differences. Differences they could not reconcile were discussed and reconciled during team meetings.

Team members also reviewed articles to identify research questions suggested either directly or indirectly. 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

Over a thirteen-week period, the team held weekly meetings to derive and adapt framework designs. Meetings during the first eight weeks involved whiteboard sketching, brainstorming, and discussing. Subsequent meetings shifted to defining and organizing framework sub-elements. In the last five weeks, separate weekly meetings were held with the above-referenced external team members. They critiqued the framework, identified gaps and ambiguities, and suggested Army-relevant additions such as environmental stressors and a team stabilization skill.

RESULTS

The CCSAF, shown in Figure 1, summarizes proficiency and expertise acquisition in complex cognitive work by individuals and teams.

Individual Proficiency and Expertise Acquisition

The CCSAF portrays basic *cognitive mechanisms* and information stores in a manner consistent with Atkinson and Shiffrin's (1968) information processing paradigm (see left blue panel in Figure 1). Basic cognition is depicted as responding to demands, pressures, and complexities of the work and work environment (see green panel) by becoming increasingly adapted to those factors. The adaptation process is represented by horizontal arrows. The attunement and adaptation of basic cognitive mechanisms (e.g., *perceptual learning*), derived cognitive mechanisms (e.g., *cognitive heuristics*), and knowledge is represented as horizontal yellow arrows. As part of their adaptation to complexity, the cognitive mechanisms and knowledge are also becoming increasingly integrated, which is represented by the large brown background arrow, to produce emergent *macrocognitive* capabilities, examples of which are listed in the brown box on the figure's right side. Our thematic analysis of cognitive elements produced additional (i.e., not listed) examples of macrocognition, including attentional control, situational awareness, using and adapting mental models, and the metacognitive skills of maintaining skepticism and systems thinking.

Our analysis also emphasized the central role of a body of rich, extensive, and highly interlinked domain-specific knowledge. The acquisition of this domain-adapted body of knowledge is represented by the yellow arrow labeled *Knowledge Integration: Chunking → Schemas → Interlinked Schemas.* Although this arrow resembles the other horizontal yellow arrows, knowledge acquisition, adaptation, and integration are foundational to improvement in the cognitive mechanisms represented by the other arrows.

Complexity in work and the work environment is defined as the consequence of nonlinearity, interactivity and dynamism, variety, ambiguity, time pressure, and factors that contribute to an inability to completely know or predict the dynamics of a given work system (e.g., Heylighen, Cilliers, & Gershenson, 2007). The task-complexity factors in the framework are drawn from work by Feltovich, Coulson, and Spiro (2001) and Wulfeck, Wetzel-Smith, and Dickieson (2003). Environmental factors were culled from the literature review and Army descriptions of complex operations (e.g., U.S. Army Headquarters, 2017).

Across the process, from left to right, cognition is depicted as interacting with and responding to the feedback of a complex work environment. Learning is a function of these interactions and feedback; it is an evolutionary and emergent process. At the same time, cognitive mechanisms and macrocognitive skills are affecting one another's development, i.e., co-evolving. Proficiency and expertise are thus represented as the co-evolutionary adaptation

of cognition to complexity in the work domain. They are forged over time and experience in response to nonlinearity, emergence, interactivity and dynamism, variety, ambiguity, time pressure, and other factors that produce a need to, for example, read cues, understand dynamics and patterns, develop strategies, tap resources, and respect limits in order to perform effectively.
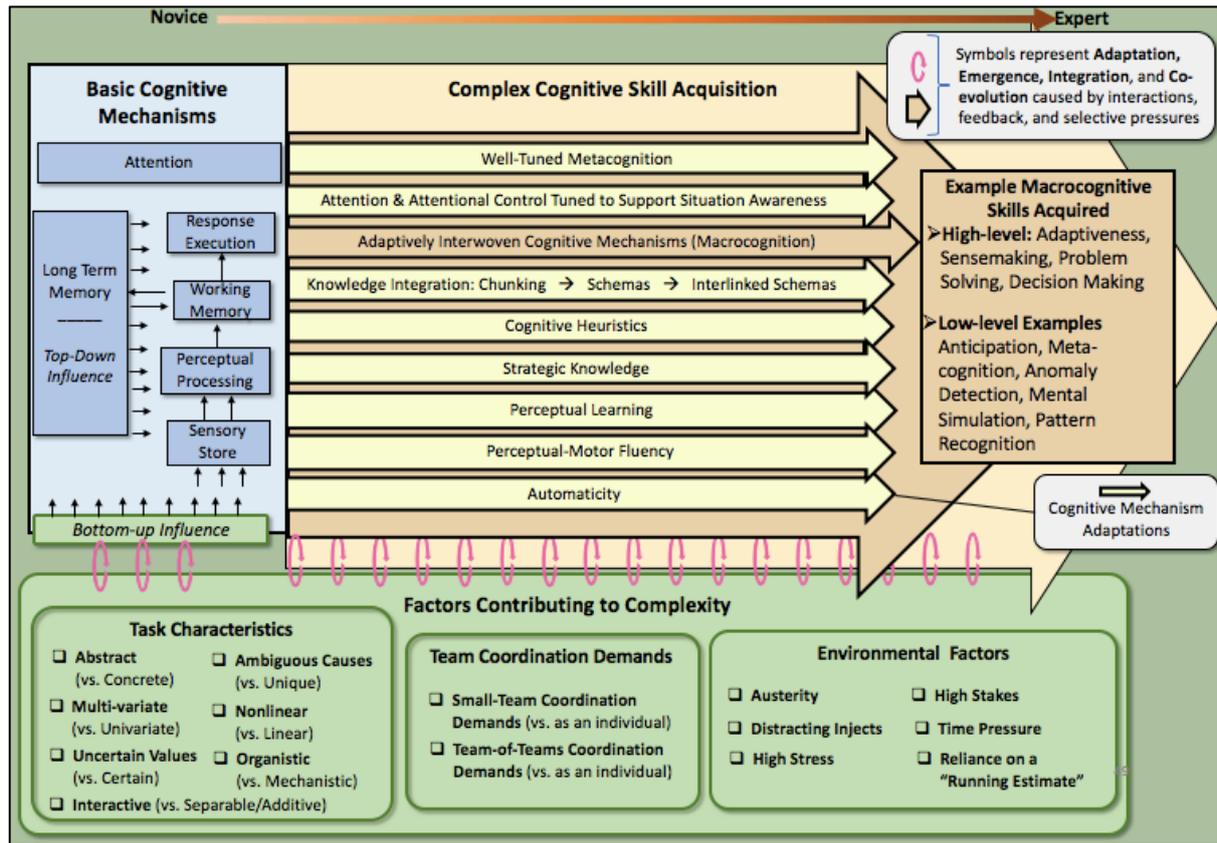
Figure 1. The representation of individual-level proficiency acquisition in the first version of the CCSAF.

Team Proficiency and Expertise Acquisition

The CCSAF also summarizes proficiency and expertise acquisition by teams that perform complex cognitive work (not depicted here due to space constraints). To represent team proficiency and expertise acquisition, team cognition adaptation is depicted in the way of individual cognitive mechanism adaptation (depicted as yellow horizontal arrows in Figure 1). It includes, as examples, the development of shared mental models, coordination strategies, transactional knowledge, and other capabilities related to team effectiveness in complex cognitive work. Individual and team cognition are depicted in the CCSAF as interacting and co-evolving. In other words, team-level proficiency growth affects the nature of individual proficiency and vice versa. Team cognition adaptations include the acquisition of joint macrocognitive skills that mirror individual macrocognitive skills shown in Figure 1 (e.g., joint sensemaking and team-level anticipation).

Research Needs

The thematic analysis of research questions revealed a need to understand more about the nature of cognitive mechanism evolution and integration. It highlighted a need to build on early progress toward the development of measures and methods for assessing and providing feedback to learners in complex cognitive work domains as they progress toward expertise (see, e.g., Hoffman and Hancock [2017] and Klein [2010]). Other needs include practical methods for facilitating expertise acquisition through advanced levels of proficiency, an improved understanding of how learning methods affect the functional integration of knowledge and skill, and methods for facilitating the growth and shaping of rich, flexible, and useful complex knowledge structures. Ward and his colleagues (2018) distill the expertise acquisition research literature to arrive at the conclusion that adaptability is the basis of advanced proficiency and expertise in complex cognitive skill and is what we should be training. They assert that further empirical work is required to evaluate the effectiveness of existing adaptativity training methods and note the need for translating the existing base of research and theory into concrete training methods and tools.

DISCUSSION

Visualization facilitates sensemaking and decision making about abstract, complex concepts (e.g., Potter, Gualtieri, & Elm, 2003). By visually representing concepts, relationships, and processes involved in complex

cognitive skill acquisition, the CCSAF can help decision makers, training professionals, and researchers alike positively impact proficiency and expertise acquisition in complex cognitive work.

We anticipate multiple CCSAF iterations driven by continued discussion and literature review. The research team has three goals for future iterations:

- Clarify the representation of research needs within and across framework elements
- Develop an improved visualization the underlying research and theory
- Explore relationships with and representation of key theories and models, such as Klein et al.'s (2003) macrocognitive processes and functions, Klein and Baxter's (2006) *Cognitive Transformation Theory*, Fiore et al.'s (2012) *Team Cognitive Readiness Framework*, and Kozlowski and Ilgen's (2006) conceptualization of team effectiveness as a function of the team's interactions with and responsiveness to complexity in the performance environment.

Within both research and practice communities, the CCSAF may foster new insights and facilitate communication and discussion. For research communities, insights may include new research questions and the recognition of new ways to think about or contribute to existing lines of research. For training practitioners, the CCSAF may facilitate the identification of work that qualifies as complex and cognitive and inform methods used to support proficiency acquisition in that work. For policy and decision makers, the CCSAF may provide a basis for decisions about training systems and programs of the future. In particular, it will provide them with alternatives to upfront, one-and-done training that are specifically suited to and effective for complex cognitive work.

ACKNOWLEDGEMENTS

REFERENCES

Atkinson, R., & Shiffrin, R. (1968). Human memory: A proposed system and its control processes. In K Spence & J Spence (Eds.). *The psychology of learning and motivation: Advances in research and theory* (Vol. 2). New York: Academic Press.

Feltovich, P. J., Coulson, R. L., & Spiro, R. J. (2001). Learners' (mis)understanding of important and difficult concepts: A challenge to smart machines in education. In K.D. Forbus & P.J. Feltovich, *Smart machines in education* (pp. 349-375). Boston, MA: MIT Press.

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.

Gobet, F. (2015). *Understanding expertise: A multi-disciplinary approach*. Macmillan International.

Heylighen, F., Cilliers, P., Gershenson, C., (2007). Complexity and Philosophy. In J. Bogg & R. Geyer (Eds.), *Complexity, Science, and Society* (pp. 117-134). Oxford: Radcliffe Publishing.

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

Hoffman, R. R., Ward, P., Feltovich, P. J., DiBello, L., Fiore, S. M., & Andrews, D. H. (2013). *Accelerated expertise: Training for high proficiency in a complex world*. Psychology Press.

Klein, G., & Baxter, H. C. (2006). Cognitive transformation theory: Contrasting cognitive and behavioral learning. *Proceedings of the Interservice/Industry Training Systems and Education Conference*, Orlando, Florida.

Klein, G. (2010). Macrocognitive measures for evaluating cognitive work. In In E. S. Patterson & J. E. Miller (Eds.), *Macrocognition metrics and scenarios* (pp. 47-64). Burlington, VT: Ashgate.

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.

Kozlowski, S. W., & Ilgen, D. R. (2006). Enhancing the effectiveness of work groups and teams. *Psychological science in the public interest*, *7*(3), 77-124.

Neville, K.J., Tenison, C., & Cowell, T.S. (2019). *An ethnographic study of knowledge building in complex work environments: Implications for knowledge capture and sharing support*. Manuscript submitted to the Annual Meeting of the Human Factors and Ergonomics Society for review.

Potter, S. S., Gualtieri, J. W., & Elm, W. C. (2003). Case studies: Applied cognitive work analysis in the design of innovative decision support. In E. Hollnagel (Ed.), *Handbook of cognitive task design* (pp. 653–678). Mahwah, NJ: Erlbaum.

Schraagen, J. M., Klein, G., & Hoffman, R. R. (2008). In J. M. Schraagen, L. Millitello, T. Ormerod, & R. Lipshitz (Eds.), *The macrocognition framework of naturalistic decision making* (pp. 3-25). Aldershot: Ashgate.

U.S. Army Headquarters (2017). *Operations* (Field Manual 3-0). Washington, D.C.: Department of the Army.

Wiltshire, T. J., Neville, K. J., Lauth, M. R., Rinkinen, C., & Ramirez, L. F. (2014). Applications of cognitive transformation theory: Examining the role of sensemaking in the instruction of air traffic control students. *Journal of Cognitive Engineering and Decision Making*, *8*(3), 219-247.

Wulfeck, W. H., Wetzel-Smith, S. K., & Dickieson, J. L. (2003). *Interactive multisensor analysis training* (RTO-MP-HFM-101: Paper 4). San Diego, CA: Space and Naval Warfare Systems Center.