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Proceedings of the Human Factors and Ergonomics Society Annual Meeting
2023, Vol. 67(1) 183–186
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DOI: 10.1177/21695067231193648
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# Cognitive Systems Engineering at 40, Part I: Deriving Theory from Practice

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**Abstract**

This expert panel is the first of a two-panel series marking the 40th anniversary of "Cognitive Systems Engineering: New Wine in New Bottles" by Hollnagel and Woods (1983) and, arguably, the beginning of Cognitive Systems Engineering (CSE). These experts were there at (or near) the beginning, devising new methods, expanding and creating new theories, and revealing a new perspective on how complex systems sustain performance and fail. They also wrestled and struggled with these new ideas to propose and implement solutions to improve performance in a number of high-consequence industries. Whether in graduate school or as early-career professionals, they saw the surprises that served as signals that the thinking that brought us to that point would not, alone, be the thinking and doing that would take us further. They will each answer the question, "What ideas and perspectives are important about Cognitive Systems Engineering, and why?"

**Keywords**

cognitive systems engineering, theory, practice

## PHILIP J. SMITH

### *Cognitive Systems Engineering as Applied to Distributed Work Systems*

At its core, Cognitive Systems Engineering (CSE) emphasizes the need to take a broader systems perspective in the design of new tools and operational concepts to deal with the constraints and competing or complementary goals of a given work domain. CSE recognizes that even when a new cognitive tool is introduced to support a particular worker, it needs to be designed with the recognition that this may result in adaptations that influence the work patterns of several interdependent people. In many cases, cognitive tools need to be designed explicitly to support the coordination and collaboration of a number of people.

The application of this CSE perspective has been demonstrated in the evolution of the air traffic flow management system in the U.S. over the last 30 years, resulting in a number of new procedures and tools to support individual and distributed work. The operational concepts that have been developed explicitly support the work of Federal Aviation Administration (FAA) Traffic Flow Managers at the FAA Air Traffic Control Systems Command Center, as well as traffic managers at the FAA's regional Air Traffic Centers and the Towers at major airports. They further support coordination and collaboration of these traffic managers with airline dispatchers. And indirectly, they affect the performance of air traffic controllers and pilots. In short, air traffic flow management and airline operations control have evolved into a highly interconnected and distributed work system that relies heavily on decision support and digital communication tools.

This evolution includes the development of procedures and tools to support Ground Delay and Airspace Flow Programs as well as the design of a National Playbook and Coded Departure Routes for coordination in managing weather and other air traffic constraints. And at present, new tools and procedures are being implemented to support Airport Surface Metering Programs and Collaborative Routing.

To support this panel discussion, Dr. Smith will provide examples illustrating the underlying design concepts that have guided the development and operation of this distributed work system. He will further discuss the realities associated with the introduction and use of these concepts.

**Philip Smith, PhD** is a Professor in the Department of Integrated Systems Engineering (ISE) at The Ohio State University. He has been teaching undergraduate and graduate

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courses in cognitive systems engineering since he started a required undergraduate course, "Introduction to Cognitive Systems Engineering" in 1983 for the ISE program. He is a Fellow of the Human Factors and Ergonomics Society and has received numerous awards, including the Air Traffic Control Association David J. Hurley Memorial Award for Research in Collaborative Decision Making. He has extensive research and development experience focusing on air traffic flow management, air traffic control, airline operations control, airport surface management, flight deck design, and the design of distributed work systems in the National Airspace System. His publications include Smith, P. J. and Hoffman, R. R. (eds.) (2018). Cognitive Systems Engineering: The Future for a Changing World. Boca Raton, FL: CRC Press.

## NANCY J. COOKE

### *Keeping the "S" in CSE*

The word "systems" in cognitive systems engineering separates CSE from cognitive psychology and cognitive science. The cognition resides not only in the head of an individual, but in components of the system and their interactions. A nuclear power plant control room is a cognitive system with cognition happening in human heads, but also in displays, decision aids, and automation and human interactions with each. As technology becomes more advanced, it can take on even more cognitive functions. The joint role of humans and machines in cognitive functioning should guide system design.

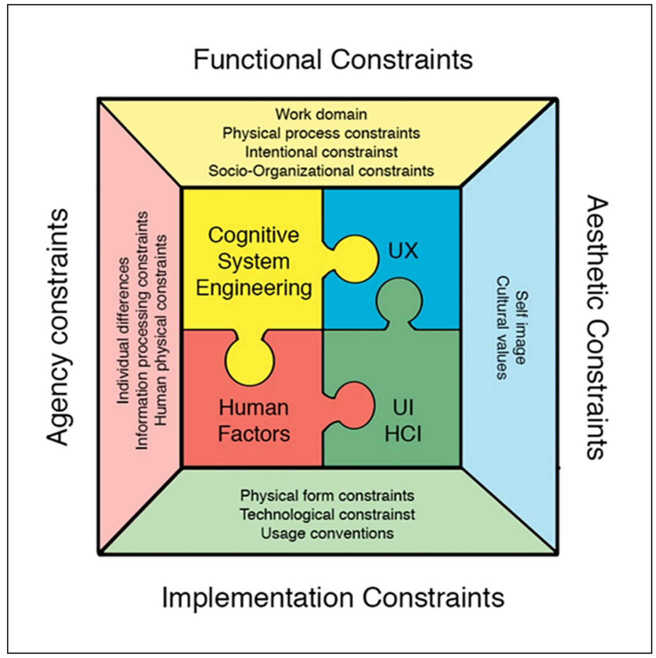
This "systems thinking" has guided my work when moving from individual knowledge elicitation to teams. Team cognition is the cognition of an interconnected and interdependent system and relies heavily on system interactions. Adding artificial intelligence and robots to the team increases system complexity, but it remains a system. This type of thinking has led to experimental manipulations, and measurements that are beyond the component level and more focused on system interactions.

**Nancy J. Cooke, PhD** is a professor of Human Systems Engineering at Arizona State University and directs ASU's Center for Human, Artificial Intelligence, and Robot Teaming. Dr. Cooke studies individual and team cognition and its application to human, AI, and robot teaming and conducts empirical assessments of teams and teamwork.

## JOHN FLACH

### *Cognitive Systems Engineering (CSE): One Piece of a New Narrative About Human-Technology Systems*

More than anything else, CSE reflects a change in how explanatory narratives about human-technology systems are framed. This new narrative is inspired by developments in theories of complexity and self-organizing systems. Specifically, it involves reframing explanations from a causal narrative that focuses on stimuli and responses, to a narrative that focuses on constraints and possibilities. While the CSE community has been a strong advocate for changing the narrative – the new narrative is bigger than the CSE story. That is, CSE is not an alternative to other approaches such as Human Factors, UX Design, and UI/HCI perspectives. Rather it is an additional perspective that contributes one piece to the new narrative. In laying out the new narrative, I want to talk about how building the full narrative depends on insights from all four perspectives: CSE, HF, UX, and UI/HCI. Figure 1 illustrates how these four different perspectives contribute to a deeper understanding of how multiple sources of constraint shape performance in human-technology systems.




**John Flach, PhD** is an Emeritus Professor at Wright State University and Principal Cognitive Systems Engineer at Mile Two LLC. His current work involves developing custom software to facilitate human decision making and problem solving in complex work domains. John has over 40 years of experience studying performance in human-technology systems. He has published extensively, including three co-authored books and four co-edited books on different aspects of cognitive systems engineering. In 2013, John received the *Paul M. Fitts Education Award* from the *Human Factors and Ergonomics Society* in recognition of his career contributions as an educator and researcher.

## ROBERT R. HOFFMAN

### *Perhaps CSE Will Be The Knight in Shining Armor*

The crucial aspect of CSE is its insistence on consideration of psychological and sociological aspects of macrocognitive work systems. Systems considerations are a core element of engineering disciplines. Beyond that, CSE emphasizes elements that have historically been neglected and even ignored in systems procurement and development. Stories are legion of badly designed technologies, from the cryptic control panel on a typical home heating and cooling system, to bedside alarm clocks lacking illuminated indicators, to home appliances lacking an "off" button. And in more recent times, horrible web page designs, cars with automation that makes things worse, not better, and so forth. One is tempted to borrow a phrase from comedian Lily Tomlin: "Things are going to get a whole lot worse before they get worse." Can CSE be the "knight in shining armor" come to set things straight?

While CSE and human factors researchers (and others) have been quick to point out these kinds of engineering gaffs, the real payoff comes from the empirical and experimental research that CSE researchers have conducted, to demonstrate the value-added. The payoff is amply illustrated by the achievements noted by the other Panelists. Perhaps CSE will be the knight in shining armor.

While singing the praises and value of CSE, an anniversary is also a time for candid retrospection. The implementation of CSE has been shaped and even marred by the same forces that drive many scientific venues. For instance, the need for clever acronyms to make ideas seem novel, the need to cater to trendy jargon, the abuse of technical terminology and scientific concepts. Fortunately, these are balanced, at least to some extent, by the anchoring of CSE in systematic empirical and experimental research, which carries with it an obligation to insist on rigor in research design and methodology. Perhaps CSE will be the knight in shining armor.

At the same time, CSE must continue to respect, and adapt to, the "fundamental disconnect": The time frames for effective and high-quality research and the time frame for influential publication are vastly outpaced by the time frame for technological advancement. Perhaps CSE will be the knight in shining armor.

**Robert R. Hoffman, PhD** is a recognized world leader in cognitive systems engineering and Human-Centered Computing. He is a Senior Member of the Association for the Advancement of Artificial Intelligence, Senior Member of the Institute of Electrical and Electronics and Engineers, Fellow of the Association for Psychological Science, Fellow of the Human Factors and Ergonomics Society, and a Fulbright Scholar. His Ph.D. is in experimental psychology from the University of Cincinnati. His Postdoctoral Associateship was at the Center for Research on Human Learning at the University of Minnesota. He has been Principal Investigator, Co-Principal Investigator, Principal Scientist, Senior Research Scientist, or Principal Author on over 60 grants and contracts including alliances of university and private sector partners. He has been recognized internationally in the fields of psychology, remote sensing, human factors engineering, intelligence analysis, weather forecasting, and artificial intelligence—for his research on the psychology of expertise, the methodology of cognitive task analysis, human-centering issues for intelligent systems technology, and the design of macrocognitive work systems. His current work focuses on "Explainable AI."

## DAVID D. WOODS

### *"New Wine in New Bottles" after 40 Years Aging: JCS Even More Potent (with some expansions)*

Erik Hollnagel and I published the first paper explicitly on Cognitive Systems Engineering 40 years ago (it was written in the latter half of 1981 and the report version appeared in February 1982 which is identical to the journal paper). Don Norman had circulated a draft called 'Steps toward Cognitive Engineering' which we saw in late 1981 as we were finishing "New Wine . . .". Our concept was far different than a mere application of cognitive science/ psychology as we continued to lay in papers and studies over the next few years. Joint Cognitive Systems as a functional unit of analysis ran counter to prevailing work on AI and subsequent attempts to solve cognitive work via algorithmic means exclusively and which continue today. We already had begun to see the fundamental brittleness of automata/AI and the failure of machine explanation which could not begin to cope with any tempo of operations. A Joint Cognitive System as an emergent functional unit highlights various forms of synchronization over roles, scopes of responsibility and time in cognitive work that made many extant proposals on how to frame the relationship between people and machine obsolete, narrow, and/ or counterproductive.

The innovation of Joint Cognitive Systems launched a program focusing on what Rasmussen called in 1981, "How Systems Adapt to Cope with Complexity." The program required a shift in methodology and analysis on how to study adapting to complexities that quickly connected to Klein's NDM, nominally standing for Naturalistic Decision Making, but really meaning that action lies in many forms of cognitive work which are not decision making (often marked as beginning with his 1986 Fire Ground Commander study). These initial concepts and findings in the 1980s continue to prove basic and, at the least, law-like: such as the Law of Demands, the Law of Fluency, Anomaly Response, etc. The set of fundamentals, including design techniques, have grown over time from studies across many complex operational settings (e.g., the Law of Stretched Systems). More importantly, the regularities observed have contributed to the rise of a new and more comprehensive synthesis in the form of Resilience Engineering which grew from CSE and several other major lines of inquiry. As a result, there are now two formal theories for how adaptive systems at human scales function despite and because of the complexities and constraints of this universe. The new formalizations achieve what Rasmussen pointed toward as he consistently emphasized the importance of adaptation and cross scale interactions.

**David D. Woods, PhD** (Professor Emeritus in Department of Integrated Systems Engineering at the Ohio State University) is one of the pioneers of Cognitive Systems Engineering (and then later Resilience Engineering) that looks at how people adapt to cope with complexity, across different roles and organizations. His work highlights the dangers of dramatic failures due to increasingly brittle systems, for example, through accident investigations in critical digital services, aviation, energy, critical care medicine, disaster response, military operations, and space operations (advisor to the Columbia Space Shuttle Accident Investigation Board). As a scientist, he has discovered the key ingredients that allow systems to build the potential for resilient performance and flourish despite complexity penalties that accompany growth (his research has been cited @42K times). As a systems engineer, he shows organizations how to uncover and overcome points of brittleness, and how to build the capability for resilient performance when, inevitably, shock events occur (e.g., awards from Aviation Week and Space Technology, Human Factors and Ergonomics Society, among others). His books include Behind Human Error, Resilience Engineering, Resilience Engineering in Practice, Joint Cognitive Systems. He started the SNAFU Catchers Consortium, a software industry-university partnership to apply the new science to build resilience in critical digital services (see stella.report ). He is Past-President of the Resilience Engineering Association and Past-President of the Human Factors and Ergonomics Society. He is frequently asked for advice by many government agencies, and companies, both domestically and abroad (e.g., DoD, NASA, FAA, IoM; Air France, TNO, IBM; UK MOD, NHS, Haute Authorité de Santé).

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