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Keeping It Too Simple: How the Reductive Tendency Affects Cognitive Engineering

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Certain features of tasks make them especially difficult for humans. These constitute leverage points for applying intelligent technologies, but there's a flip side. Designing complex cognitive systems is itself a tough task.

Cognitive engineers face the same challenges in designing systems that users confront in working the tasks that the systems are intended to aid.

Research background

Research conducted under the rubric of Cognitive Flexibility Theory examined learning and performance in medical education and, in particular, how people learn and understand the cardiovascular system.[1,2] The research identified characteristics of learning material and performance situations that cause cognitive difficulty for learners and operators. It also determined how people respond to these elements of difficulty. That research found that learners and practitioners often deal with complexity through oversimplification, which can lead to misconception and faulty knowledge application.

The dimensions of difficulty

Eleven dimensions make tasks difficult and require mental effort.

Static vs. dynamic. Are important aspects of a situation captured by a fixed "snapshot," or are the critical characteristics captured only by the changes from frame to frame? Are phenomena static and scalar, or do they possess dynamic, vector-like characteristics?

Discrete vs. continuous. Do processes proceed in discernable steps, or are they unbreakable continua? Can we describe attributes by using a few categories (for example, dichotomous classifications such as large/small), or must we recognize and use continuous dimensions (such as size) or numerous categorical distinctions?

Separable vs. interactive. Do processes occur independently or with only weak interaction, or do strong interaction and interdependence exist?

Sequential vs. simultaneous. Do processes occur one at a time, or do multiple processes occur at the same time?

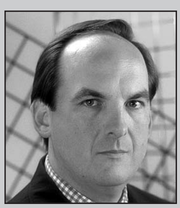
Homogeneous vs. heterogeneous. Are components or explanatory schemes uniform (or similar) across a system, or are they diverse?

Single vs. multiple representations. Do elements in a situation afford single or just a few interpretations, functional uses, categorizations, and so on, or do they afford many? Do we need multiple representations (such as multiple perspectives, schemas, analogies, models, or case precedents) to capture and convey the meaning of a process or situation?

Mechanism vs. organicism. Are effects traceable to simple and direct causal agents, or are they the product of more systemwide, organic functions? Can we gain important and accurate understandings by understanding just parts of the system, or must we understand the entire system to understand even the parts well?

Linear vs. nonlinear. Are functional relationships linear or nonlinear (that is, are relationships between input and output variables proportional or nonproportional)? Can a single line of explanation convey a concept or account for a phenome-





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non, or does adequate coverage require multiple overlapping lines of explanation?

Universal vs. conditional. Do guidelines and principles hold in much the same way (without needing substantial modification) across different situations, or does their application require considerable context sensitivity?

Regular vs. irregular. Does a domain exhibit a high degree of regularity or typicality across cases, or do cases differ considerably even when they have the same name? Do concepts and phenomena exhibit strong elements of symmetry and repeatable patterns, or is there a prevalence of asymmetry and an absence of consistent pattern?

Surface vs. deep. Are important elements for understanding and for guiding action delineated and apparent on the surface of a situation, or are they more covert, relational, and abstract?

The consequences of complexity

The research also revealed serious consequences when the material to be learned or understood exhibits the latter alternative in each of the above 11 dimensions—that is, when

- Events are dynamic, simultaneous and parallel, and organic (evolving, emergent) rather than governed by simple cause and effect
- Event parameters are continuous and highly interactive
- Events involve heterogeneous components or explanatory principles, nonlinear dynamics, and multiple context-dependencies
- Events can be understood by multiple representations
- Cases show asymmetries and irregularities
- Key principles are abstract and nonobvious

In such cases,

- Learners and practitioners tend to interpret situations as though they were characterized by simpler alternatives
- Their understandings tend to be reductive—that is, they tend to simplify
- They tend to try to defend their simple understandings when confronted with facts that suggest that the situation is more complex than what they suppose
- Overcoming these defenses requires practice, experience, and mental effort

The reductive tendency

The term *reductive bias*[3] has been used to describe people's inclination to construct overly simplistic understandings and categories. However, we do not see this as a bias in the sense in which cognitive science frequently uses the term. Rather, this reductive tendency is an inevitable consequence of how people learn.[4] Of necessity, when people are forming a new understanding or developing a new category, their knowledge is incomplete. How else could it be? People perceive, understand, and learn distinctions only through additional experience and thought. So, at any point in time, a person's understanding of anything that's at all complex, even domain experts' understandings, is bound to be simplifying at least in some respects.

When learners are confronted with evidence contrary to their views, they perform mental maneuvers to rationalize their faulty beliefs without fundamentally altering them.

In areas of complex cognition, the reductive tendency can lead to significant misconceptions and error-ridden performance.[5] In addition, the misconceptions might resist change. When learners are confronted with evidence contrary to their views, they perform mental maneuvers to rationalize their faulty beliefs without fundamentally altering them. These protective operations are called *knowledge shields*, and researchers have identified 23 of them.[5]

One such shield is the *demean effect*. When confronted with the evidence, learners acknowledge that the evidence might be true but dismiss it as trivial—"it's not a big deal." Here's an example:

> Instruction: As a vessel expands during the ascending phase of a pulse, this doesn't mean that all the blood in the expanded vessel simply flows downstream through a now larger vessel, since some of it, for instance, flows into the expansion of the vessel itself.
>
> Student response: (long pause) "Um, I'm going to agree. It makes sense that some of it would flow into the expansion of the vessel, but I'm sure it's not a big part of it."

Two other knowledge shields are *argument from faulty causal reasoning* and *extirpation*. In the first, the learner constructs a false causal explanation, consistent with his or her belief, for the anomalous evidence. In the second, the learner isolates the phenomenon to be explained from its real context. In the following example, the student uses both shields to avoid a real change in belief:

> Instruction: In the pulsing cardiovascular system, some of the energy produced by the heart is used up in making blood flow into and out of the expansion of vessel walls. Hence, factors associated with flow into and out of the vessel walls, such as stiffness and heart rate, contribute to opposition to blood flow.
>
> Student response: "And I agree with that, um, because when blood goes into the expanded area and then that expanded area contracts, the blood's gonna go both forward and backward, and this is going to create opposition to the other blood coming in."

Although Cognitive Flexibility Theory and the reductive tendency first had their impact in medical education, they have found wider application.[6,7] In particular, they have implications for our own understanding of the nature of *complex sociotechnical systems*. That is, what if our own (that is, cognitive engineers') understanding of CSSs is itself subject to a reductive tendency?

The nature of complex sociotechnical systems

CSSs are workplaces in which individuals act as collectives with the support of information technology, to conduct cognitive work.[8,9] Cognitive work involves obtaining, using, and sharing knowledge in the pursuit of goals under changing circumstances. Goals include empowering others to act according to that knowledge or a certain state of situation awareness. David Woods and his colleagues have identified consistent patterns ("Laws That Govern Cognitive Work") to activities and problems in CSSs, and to the principles governing human-machine interaction in cognitive work.[10,11] Previous installments of this department have presented some of these as principles of human-centered computing.

CSSs don't sit still, in at least two respects. First, new technologies provide new capabilities, but these spawn new expectations, roles, and ways of doing things. They can also introduce new complexities—for example, increased interconnectedness, interdependency, and need for coordination among players. Workers will employ various adaptations, including work-arounds, to function successfully in the new environment.[12] As Woods has written, "Whatever the artifacts and however autonomous they are under certain conditions, people create, operate and modify these artifacts in human systems for human purposes."[10]

Second, all the workplace participants operate from personally constructed models of the work to be done and of the other parties involved, including their roles, capabilities, and needs. This means that the CSS is inhabited by multiple viewpoints, multiple value systems, multiple ways of operating, multiple assessments of responsibility and authority, and the like. Different people will model the work environment's key elements differently, depending on such things as their backgrounds, experiences, responsibilities, personal agendas, and particular tasks.

This portrayal involves considerable complexity, including

- Constant readaptation, and hence constant dynamics and change
- Strong interaction and interdependence of processes and people
- Multiple interpretations, ambitions, and viewpoints
- Heterogeneous capabilities and methods
- The need to interpret and respond appropriately to high degrees of context sensitivity

This characterization of the complex workplace, at a general level, conforms precisely with the 11 dimensions of difficulty.

The implication for cognitive engineering: The "envisioned world" problem

If the reductive tendency affects the design, and redesign, of CSSs in the same ways it affects other complex domains of learning and knowing, what are the implications?

Static/dynamic

If the reductive tendency affects this dimension, cognitive engineers would be prone to construe dynamic situations as more static than they really are. The reductive assumption for CSSs would be that the way work is carried out might be improved but will be fundamentally the same after an intervention. This reduction probably also construes the day-to-day practice of work as being more routine than it actually is.

Discrete/continuous

The reductive tendency on this dimension would treat continuous processes as being more incremental than they really are. The cognitive engineer might be prone to think of continuous processes in terms of discernable steps. Perhaps most important, cognitive engineers might fail to anticipate that adaptive change will occur at all, and if it does, they might think that it consists of easily detected stages or steps.

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Separable/interactive

Here, the reductive tendency would treat processes and people as functioning more in isolation and insulation than they actually do. The cognitive engineer might fail to appreciate the widespread interdependency of effects across workplace components. The reductive assumption would be that changing a component of the workplace would have only local, contained effects that wouldn't ripple throughout the operation following an intervention.

Sequential/simultaneous

The reductive tendency for this dimension resembles that for separability/interactiveness. However, here it emphasizes thinking of the work practice as a linear set of workplace steps, as in an assembly line, rather than a matter of interactiveness and simultaneity. This reductive assumption can, and often does, result in technologies that impose difficulties in coordination and communication, and in building common ground. This leads designers to be confident that demands for coordination have been reduced, whereas when the system is in use, the practitioners experience automation "surprises."

Homogeneous/heterogeneous

The reductive tendency would result in assumptions that the processes, values, ways of doing things, cultural norms, abilities, loyalties, and so forth are pretty much the same across the many diverse units of the CSS—a kind of uniformity tendency. This reduction's effect in design would be that the cognitive engineer fails to anticipate the diversity of reactions and adaptations to a workplace change.

Single/multiple representations (functions)

The reductive tendency would occur when the cognitive engineer doesn't realize that appraisals of the CSS, before and after an intervention, can vary greatly among different stakeholders. For example, a system's usability can vary across different perspectives, both with regard to the operation of the workplace itself (for example, its profitability, degree of stress, efficiency, and quality) and from the viewpoint of different stakeholders (for example, management, workers, unions, shareholders, the US Occupational Safety & Health Administration, and the US Internal Revenue Service). This tendency would also involve various kinds of fixations on the cognitive engineer's part—that is, envisioning the future (for example, how some device will be used or how some group will react to a change) in a rigid, fixed way.

Mechanism/organicism

The reductive tendency would treat CSS operation as a set of low-level, direct causes and effects. It would involve no consideration of complex, nonlinear, interactive, self-organizing characteristics that can emerge because the CSS has qualities and processes that are more than the sum of its component parts.

Linear/nonlinear

The reductive tendency would involve the assumption that changes, effects of interventions, and perturbations of various kinds to the CSS will have incremental, manageable consequences. This would entail failure to account for or anticipate the effects of tight coupling that produce cascading effects and other nonlinear responses. As a result, for example, developers can miss the complexity induced by the coupling (for example, how effects-at-a-distance complicate diagnostic reasoning), and their designed system would leave the practitioner unsupported.

Universal/conditional

The reductive tendency would be the assumption that a design principle has the same applicability and effects throughout the many different and changing contexts of work and practice. That is, the effects, embodied in the design principle, will hold fairly universally across differing practice environments. Indeed, one can sense this reductive tendency in operation in previous essays in this department.

The reductive tendency at work in design and envisionment

An example of how the reductive tendency affects the design of CSSs appears in the discussion of the "substitution myth."[13] As David Woods and his colleagues note frequently, the myth is that when some work system component is replaced by some device, the work's fundamental nature will remain essentially the same. That is, the replacement device will function in much the same way that the original component did (although it might be faster, more efficient, and so on). This is almost never the case; the work system changes dramatically, often in unintended, unanticipated, and undesirable ways.

Clearly, we can attribute the substitution myth's pervasiveness to the reductive tendency affecting designers on several of the dimensions of difficulty. For example, the myth involves treating dynamic work as static, treating interdependencies as being compartmentalized, and regarding the irregular nature of work as more regular and routine than it is.

So, what can we do about this? Is simple awareness of the reductive tendency and the dimensions of difficulty enough?

Mitigating the reductive tendency

Knowledge of the oversimplifications that designers will likely commit in CSS environments should influence the creation of intelligent instructional and performance support tools. This is already happening. There are systems that seem to acknowledge, and avoid, reductive tendencies. There are tools that help operators comprehend the implications of numerous, interdependent, and constantly changing variables that affect successful execution of a task—for example, flying an airplane.[14] Devices exist that warn doctors and patients about adverse interactions among drugs and activities. Instructional systems based on Cognitive Flexibility Theory are being built to help learners analyze and comprehend difficult material from multiple viewpoints.[15]

But the dimensions of difficulty themselves should provide explicit guidance for cognitive engineers who are confronted with challenges in CSS design. The dimensions, as well as people's known reactions to them, might help suggest leverage points, strategies, heuristics, and even technologies to help the cognitive engineer overcome reductive tendencies and effectively explore the envisioned world. A great opportunity exists here for creating tools that help those who design CSSs to anticipate and plan for the effects on work practice to be expected from new designs or redesigns.

Knowledge of the oversimplifications that designers will likely commit in CSS environments should influence the creation of intelligent instructional and performance support tools.

Finally, we must assume that cognitive engineers will invoke one or more knowledge shields when they're confronted with evidence that their understanding and planning involves a reductive understanding. The knowledge shield phenomenon suggests that it will take effort to change the reductive mindset that people might bring to designing a CSS and envisioning its nature after an intervention. ■

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References

1. P.J. Feltovich, R.J. Spiro, and R.L. Coulson, "Issues of Expert Flexibility in Contexts Characterized by Complexity and Change," *Expertise in Context: Human and Machine,* P.J. Feltovich, K.M. Ford, and R.R. Hoffman, eds., AAAI Press, 1997, pp. 125–146.
2. R.J. Spiro et al., "Cognitive Flexibility Theory: Advanced Knowledge Acquisition in Ill-Structured Domains," *Proc. 10th Ann. Conf. Cognitive Science Soc.*, Lawrence Erlbaum Associates, 1988, pp. 375–383.
3. P.J. Feltovich, R.J. Spiro, and R.L. Coulson, "The Nature of Conceptual Understanding in Biomedicine: The Deep Structure of Complex Ideas and the Development of Misconceptions," *Cognitive Science in Medicine*, D. Evans and V.L. Patel, eds., MIT Press, 1989, pp. 113–172.
4. J. Feldman, "The Simplicity Principle in Human Category Learning," *Current Directions in Psychological Science*, vol. 12, no. 6, 2003, pp. 227–232.
5. P.J. Feltovich, R.L. Coulson, and R.J. Spiro, "Learners' (Mis)understanding of Important and Difficult Concepts: A Challenge for Smart Machines in Education," *Smart Machines in Education: The Coming Revolution in Educational Technology*, K.D. Forbus and P.J. Feltovich, eds., AAAI Press, 2001, pp. 349–376.
6. R.I. Cook and D.D. Woods, "Operating at the Sharp End: The Complexity of Human Error," *Human Error in Medicine*, M.S. Bogner, ed., Lawrence Erlbaum Associates, 1994, pp. 255–310.
7. C.E. Hmelo-Silver and M.G. Pfeffer, "Comparing Expert and Novice Understanding of a Complex System from the Perspective of Structures, Behaviors, and Functions," *Cognitive Science*, vol. 28, no. 1, 2004, pp. 127–138.
8. J.M. Carroll and M.B. Rosson, "Getting around the Task-Artifact Cycle: How to Make Claims and Design by Scenario," *ACM Trans. Information Systems*, vol. 10, no. 2, 1992, pp. 181–212.
9. T. Winograd and F. Flores, *Understanding Computers and Cognition*, Ablex, 1986.

10. D.D. Woods, "Steering the Reverberations of Technological Change on Fields of Practice: Laws That Govern Cognitive Work," *Proc. 24th Ann. Meeting Cognitive Science Soc.*, Lawrence Erlbaum Associates, 2002, pp. 14–17.

11. D.D. Woods and S.W.A. Dekker, "Anticipating the Effects of Technological Change: A New Era of Dynamics for Human Factors," *Theoretical Issues in Ergonomic Science*, vol. 1, no. 3, 2000, pp. 272–282.

12. P. Koopman and R.R. Hoffman, "Work-arounds, Make-Work, and Kludges," *IEEE Intelligent Systems*, vol. 18, no. 6, 2003, pp. 70–75.

13. K. Christoffersen and D.D. Woods, "How to Make Automated Systems Team Players," *Advances in Human Performance and Cognitive Engineering Research*, vol. 2, E. Salas, ed., JAI Press/Elsevier, 2002, pp. 2–12.

14. A. Gerold, "OZ: A Revolution in Cockpit Display," *Aviation Magazine*, Oct. 2003, pp. 27–32.

15. R.J. Spiro et al., "Cognitive Flexibility, Constructivism, and Hypertext: Random Access Instruction for Advanced Knowledge Acquisition in Ill-Structured Domains," *Educational Technology*, vol. 31, no. 5, 1991, pp. 24–33.

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