1 Cognitive Engineering and Its Relationship to Future Aviation Systems

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ABSTRACT

The discussion of Cognitive Systems Engineering (CSE) presupposes two things. First, that military aviation systems are susceptible to cogminutia fragmentosa. One of the hallmarks of cogminutia fragmentosa is that the user of a system cannot effectively adapt to encountered situations. This inability is due to a mismatch between the human's understanding of the current situation's properties, potentiality, and constraints and the actual state of the real world. One of the best examples of the problem is the difficulty that has been experienced in effectively using automation to aid pilots. The second assumption is that the application of cognitive systems engineering to the design of military aviation systems is a likely palliative for the problem. For example, to improve the situation with automation, it must become more sophisticated in its interactions with the human team members. This more sophisticated and cooperative future automation has been referred to as an Electronic Associate (EA). Designing the EA demands a much better understanding of the human crew so that the EA can work well with the crew. CSE may provide the insights to accomplish this goal. It is vital that useful tools for avoiding cogminutia fragmentosia be developed and validated because pilots of future military aircraft will be confronted with even more capable and complex systems to control. Also, some future systems, such as the Unmanned Combat Aerial Vehicle (UCAV), will be moving the operator completely out of the aircraft. Using CSE should be tested as a means for designing such challenging and important future systems.

1.1 INTRODUCTION

To understand the nature of the following paper, it is first necessary to appreciate the context in which it was written. I was asked to give an opening address to welcome the delegates to the CSE Workshop. Following my address, I was asked to write this paper. The paper reflects my address, and does not discuss the latest developments in CSE. However, it does show some potential payoffs that cognitive systems engineering can bring to the aviation arena.

As I read the title of the workshop, "Cognitive Systems Engineering and Military Aviation Environments: Avoiding Cogminutia Fragmentosa!," I became curious as to the meaning of "cogminutia fragmentosa." I began reading the abstract carefully and came across a major implication—if the user suffers from this phenomenon, "the user cannot properly *adapt* to the situation encountered." Since one of the goals of future systems is to have both the operator and the machine adapt, serious problems can result. Fortunately, the abstract reports that CSE is the "method or tool of choice to respond to work environments that produce cogminutia fragmentosa." Following this logic, CSE will have a major impact on future systems. In the discussion that follows, I hope to show that this premise is indeed true.

1.2 PROBLEMS WITH CURRENT SYSTEMS

Aviation Week and Space Technology (1995) published a special issue regarding automation concerns in commercial aircraft. One of the concerns was automation surprises, that is, the operators did not know why the automation was performing various tasks. They could not penetrate the decision logic. The reason for this problem is shown in Figure 1.1, and it centers around the mental distance between the operator input and the system output.

In older aircraft, there was a direct connection between the pilot's movement of the control yoke, through the connecting cables, to the control surfaces. Later as autopilots came in to the aircraft, the pilots indirectly controlled the surfaces through these devices. Further, with the introduction of flight management systems, more technology was placed between the pilot and control surfaces. The pilot's mental model of how the system worked became severely strained and resulted in a lack of understanding of the relationship between the automation and the control output. Some of these cockpit problems were undoubtedly due to the automation philosophy which drove the task sharing between the crew and the automation.

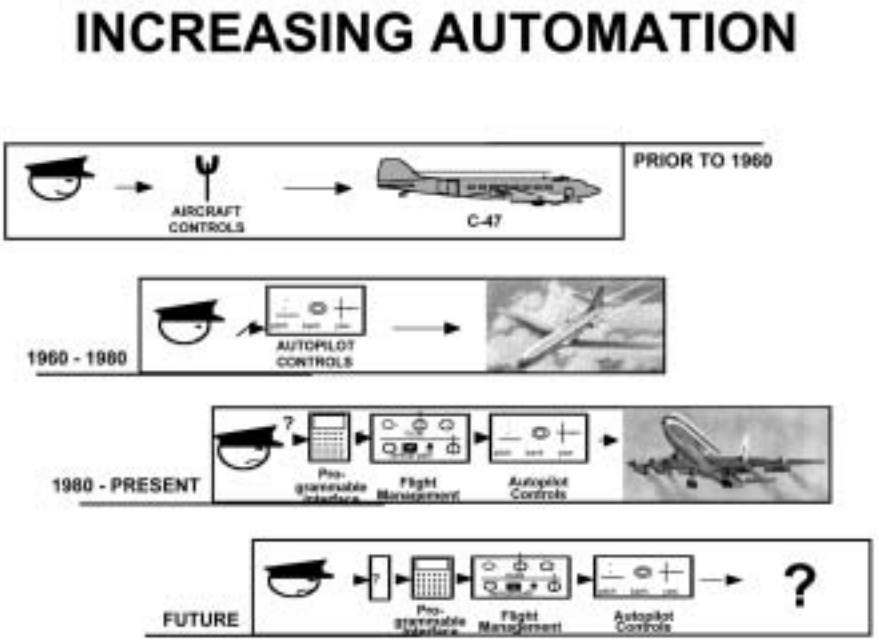

Figure 1.1: Impact of automation on increasing mental distance between operator input and system output.

1.3 PHILOSOPHY OF AUTOMATION

1.3.1 Early Automation Philosophy

"…It appears that the best arrangement is one in which inanimate components work as a team with human operators to provide safe and accurate control and guidance" (Draper, Whitaker, & Young, 1964, p. 5). The key concept in this philosophy is that the operator and the machine form a team. The active participation of the operator, a key component of the teaming arrangement, was reinforced in 1966, in a paper by Knemeyer and Yingling of the Air Force Flight Dynamics Laboratory. They expressed the thought that we cannot expect pilots, in an emergency, to cope with a problem which they have not been following. By monitoring only and not performing, they will fail to notice important information and, consequently, will not react properly (Knemeyer & Yingling, 1966). They went on to assert that automation is desirable, and it should exist not as a conflict but as an aid, an adjunct to the pilot.

For several years (early to mid-1960s) the Air Force research and development community pursued a technically sound and logical solution to the

pilot/autopilot integration problem. The concept was first evaluated by the Germans during World War II and was introduced in this country with names such as "pilot control force steering" or "force wheel steering." The system linked the pilot to the control surfaces through the autopilot by placing electronic force sensors in the control column and rudder pedals of the aircraft. The control pressures applied by the pilot were converted to electronic signals which were sent to the autopilot computer where they were summed with the commands being provided by the basic flight director system to, in turn and accordingly, move the control surfaces. This system provided the means for the pilot, in an emergency or otherwise, to assume control of the aircraft smoothly and in a conventional fashion without having to uncouple or disengage the autopilot. To a certain extent this concept has been overcome by the introduction of computer controlled "fly-by-wire" flight control systems in which the pilot provides inputs to the flight control computer which sums them with inputs from the aircraft's attitude sensors and manipulates the control surfaces to provide the required flight vector. However, this does not provide the pilot with the degree of autopilot control visualized in the original force wheel steering concept.

1.3.2 Today's Automation Philosophy

Despite the work in the early 1960s, the team arrangement design philosophy has rarely, if ever, been carried out in the implementation of automation in today's aircraft systems. To create teamwork, the designer must examine the roles of the human and machine in the system (Gagne, 1962). One of the key components in this process is function allocation between the human and the machine. Ideally this division of responsibilities between the two "team members" occurs by taking into account the strengths and weaknesses, workload limitations, etc., of each and then assigning their roles accordingly. However, in actual system design that is not how the process usually occurs; function allocation is largely a myth and is rarely applied in system design and development (Fuld, 1993). What basically happens is that everything possible is automated, and the human operator gets left with doing what the machine cannot do or what the machine fails to do because of a malfunction.

"Somewhat paradoxically, machines that can do more, and do it faster, provide the basis for systems that are increasingly demanding of the human operator, particularly in terms of cognitive requirements" (Howell, 1993, p. 235). The demand comes about because the operator is "not in the loop," but rather is a bystander—so long as the system functions normally. When emergencies occur, the operator is expected to take control of the system, diagnose the problem, and bring the system back to the nominal state. However, as was discussed in Section 1.1, a design driver should be to make the operators an

integral part of an automated system so they can adapt properly and avoid cogminutia fragmentosa to bring the system back to the nominal state. In other words, what is needed is adaptive allocation. "In this form, a change in allocation is triggered by some change in, for example, the performance level of the human operator. Particular concern is given to prevention of task overload (or, conversely under load) imposed on the human" (Hancock, 1996).

1.3.3 Future Automation Philosophy

It is interesting to note that nearly thirty years after the teamwork automation philosophy was espoused, it has once again come to the forefront. The term currently used is *human-centered automation* (Billings, 1991), which starts with the operator as the heart of the system and then incorporates the automation. From the operators' point of view automation is designed as it should be—to augment or assist operators in areas where they show limitations (Wickens, 1993). Although this automation philosophy is consistent with earlier years, the implementation can be much more difficult because many more avionics systems are contained aboard modern combat aircraft. On the other hand, because of present day capabilities in computers and software, the resulting product can be much closer to a true team. Operator-machine relationships are created which emulate those occurring between two human crewmembers—mutual support and assistance. This support can come about through a sophisticated decision aid which I will now call an Electronic Associate (EA).

1.4 OPERATOR AND ELECTRONIC ASSOCIATE ARE A TEAM

To function effectively, the operator and the EA must work together as a close-knit team. The ideal relationship between operator and machine can be likened to that of the good manager and his staff. The manager must be sufficiently aware of the work of the staff to be able to predict problems, but not so involved that their work is hindered. He must be involved enough to be able to offer assistance when called upon, and yet the manager must not micromanage and risk becoming overloaded and prevented from making the strategic decisions. The good manager will know which staff members can be relied on to act without supervision, as the pilot will form opinions about which of the aircraft systems require frequent attention. As in the conventional management situation, the aircraft's EA system must maintain the knife-edge balance of providing sufficient data exchange without swamping the pilot system manager; allowing sufficient machine autonomy without alienating the manager; and providing sufficient control without overloading the manager.

It must be remembered that the EA will be performing many of the functions now allocated to the second human crewmember in today's military aircraft such as a Royal Air Force's GR–1 Tornado or a U.S. Air Force's F–15E Strike Eagle. The effectiveness of these aircraft is significantly affected by the degree to which the two human crewmembers become an integrated team. Southeast Asia experience with F–4 Phantoms demonstrated this to be the case. With changing crewmembers, a conscious effort to build up the team relationships was critical. The problem arose because crew rest, illness, sortie generation requirements and individual rotation schedules precluded the same team from flying together on each mission. The result was that often a pilot and weapons system officer, who had not worked together before, were paired for a particular mission. Time and again it was proven that learning the individual aspects of each team member became an important factor in a successful mission.

1.4.1 Team Trust

One essential feature of a successful team is trust in the other partner. This in turn implies that the partner behaves in a rational and reliable manner; a partner cannot initiate actions which, even though they are logical to one, appear to be illogical to the other. To avoid arbitrary actions, there must be some overall governing rules which provide the logical structure under which both members operate. As examples of explicitly stated governing rules, consider the three laws of robotics (Asimov, 1950).

- A robot may not injure a human being, or through inaction, allow a human being to come to harm
- A robot must obey the orders given to it by human beings except where such orders would conflict with the first law
- A robot must protect its own existence as long as such protection does not conflict with the first or second law.

These rules provide the guidance required to allow the robot to perform its job in a reasonable and consistent manner. If the word "pilot" is substituted for the word "human" in the above example, a possible basis for governing the behavior of the EA exists. The three laws stated above are only examples of governing rules, and they would require major changes to be applicable in a military setting. For instance, without modification the ideal robot would not allow the pilot to take off, knowing that he was deliberately going in harm's way. The point is, however, that rules of this type provide the basis for consistent behavior for the EA and thereby provide a basis of trust for the pilot. It is through this trust that an effective team can be built. However, trust is not acquired instantaneously; it must be built up gradually. Trust can be envisioned

to develop in three stages. At first trust is based on the predictability of individual behaviors. In the second stage trust is based on dependability. "…Dependability may be thought of as a summary statistic of an accumulation of behavioral evidence, which expressed the extent to which a person can be relied upon" (Muir, 1987, p. 532). In the third stage of trust, faith is the major component because one team member is willing to bet that the other member will be dependable in the future.

Once the trust is built between the crew member and the EA, the continued overall efficiency of the system depends on such factors as machine accuracy, compliance with the suggestions of the EA, and degree of faith in the continued accuracy of the decision aid (Raeth & Reising, 1999; Riley, 1989).

1.5 BUILDING THE ELECTRONIC ASSOCIATE

One of the primary goals of the U.S. Air Force's Pilot's Associate Program was to create a software helper to better enable the operator to cope with the increasingly complex automation. The level of autonomy given to the software helper was that of an associate. "The 'associate relationship' is characterized by a mixed-initiative approach to collaborative problem solving between one or more human actors and a subordinate but semiautonomous computer system with sufficient depth and range of intelligence and capabilities to accomplish a full task domain" (Miller & Riley, 1995).

Analogous to Asimov's three laws of robotics, Principles of Interaction (Lizza, Rouse, Small, & Zenyuh, 1992) were created in the Pilot's Associate

The Effort to Require of the Pilot to Control the PA Must Be Less Than the Effort Saved by the PA.

Plans May Be:

- Approved or Rejected Explicitly
- Approved or Rejected Pre-Mission
- Approved or Rejected Implicitly by Pilot Action
- Ignored, with Predictable Results
- The PA Must Operate In a Predictable Manner.
- All PA Actions Must Be Tailorable by the Pilot.
- The PA Is Required to Monitor the Pilot, Not the Other Way Around.
- The PA Must Follow the Pilots Lead.

Figure 1.2: Examples of rules to specify the relationship between the pilot and pilot's associate (PA).

Program, which would specify some of the operating rules between the pilot and the EA. A partial list can be seen in Figure 1.2.

One of the major ways to assist the operator is seen in the statement, "The PA is required to monitor the pilot, not the other way around." The same philosophy was carried on in the Rotorcraft Pilot's Associate RPA program conducted by the U.S. Army. The philosophy was expanded in that not only would the EA monitor the operator's performance, but would also understand the commander's *intent* and plan accordingly. One way of understanding the commander's intent is to look at the strategies employed in performing particular tasks. Cognitive Task Analysis (CTA) is well-suited for this arena. "…CTA attempts to discover the strategies that people actually use to perform a task, along with the cues and relationships and patterns required by the strategies" (Klein, 1995, p. 530).

The key result of the monitoring and planning is the ability of the EA to off-load tasks from the air crew in times of high workload. For the EA to achieve this, a very detailed cognitive task analysis is required to determine which tasks the crew is required to perform in the course of the mission. Once the task model is programmed, the EA can then monitor the task model as a basis for nominal performance. If the crew falls behind in performing these tasks because of the uncertainties involved in actual combat situations, the EA can then aid the crew by assuming the tasks they shed. The RPA was successfully flight tested, and various functions of the associate were exercised. Since the completion of the RPA program, the U.S. Air Force and the Defense Advanced Research Projects Agency, along with Boeing, have decided to incorporate the RPA's associate's software into the Unmanned Combat Aerial Vehicles (UCAV) program (Dornheim, 1999).

1.6 UNMANNED COMBAT AIR VEHICLE (UCAV) AND THE ELECTRONIC ASSOCIATE

The U.S. Air Force, as well as a number of other countries, has an unmanned reconnaissance vehicle in operational status. The Predator is in the Air Force inventory, and it is planned that another vehicle, Global Hawk, will also soon enter operational status. These types of vehicles are used for a variety reconnaissance and intelligence gathering activities. Their performance in Bosnia has proven to be very worthwhile, and new platforms are under development (*Aviation Week & Space Technology*, 1996; Goodman, 1996). Further in the future, a combat version of an uninhabited vehicle is a strong possibility. In fact, the creation of a combat vehicle was one of the major recommendations of the *New World Vistas (NWV): Air and Space Power for the 21st Century* report. "An effective UCAV will be enabled in the next century as the result of the simultaneous optimization of information flow, aircraft performance and

mission effectiveness" (McCall & Corder, 1995, p. 34). Lest anyone think the inhabited aircraft is a thing of the past, the report goes on to say, "The UCAV will not completely replace the inhabited aircraft for decades, if ever, but the presence, or absence, of a pilot is now a design trade that can be made in a logical way" (McCall & Corder, 1995, p. 34).

One reason these vehicles are being considered is performance. Without having to take into account the physical limitations of the pilot, UCAVs could be designed to pull 10 to 20 times the force of gravity, something not possible in inhabited aircraft (Fulghum, 1996). This increased performance, in turn, enhances survivability for the vehicle. The operator's survivability will also be increased, since he or she will be remote from the UCAV.

1.6.1 Operator's Station

There are at least three different stations being contemplated, depending on the operator's distance from the UCAV—the back seat of a two-seat fighter/attack aircraft (as exemplified by current aircraft such as the F–15E Strike Eagle or the Tornado GR1), one of the crew of an airborne command and control aircraft, or at a ground location. The first would be closest to harm's way since the fighter/attack aircraft could be in the battle area, but somewhat removed from the ground target. The second would be further from the target area and would be in an aircraft flying over friendly territory. The third could be in enemy territory, but just as likely would be in friendly territory at some considerable distance from the target area. In each of the three operator stations, the operators would have to be given information sufficient to provide them with the situation awareness needed to successfully complete the mission.

The ground-based operator's station located far from the battle area may pose the most difficult challenge in providing adequate information to the operators. Various sensor assets would have to be combined with databases to give them both a general overview of battle area as well as a real time "view" of the target area. Head-mounted displays and projection systems are two possible candidates for providing a synthetic 3-D world to the operators. The mode of operator control could be through voice, hand motion wearing a 3-D cursor controller such as a data glove, or some bezel mounted keys on real, panel-mounted displays. Regardless of how the operators interface with the station, physical requirements of the ground-based operator station would be less than its airborne counterpart which has to undergo the rigors of flight.

The overwhelming number of tasks for the operator of the ground-based UCAV control station will be cognitive rather than physical. Being remote from the vehicle, the operator will not experience any of the physical stresses imposed by the flight regime; however, to stay aware of the vehicle status and its progress in the mission, the operator may have a high cognitive load.

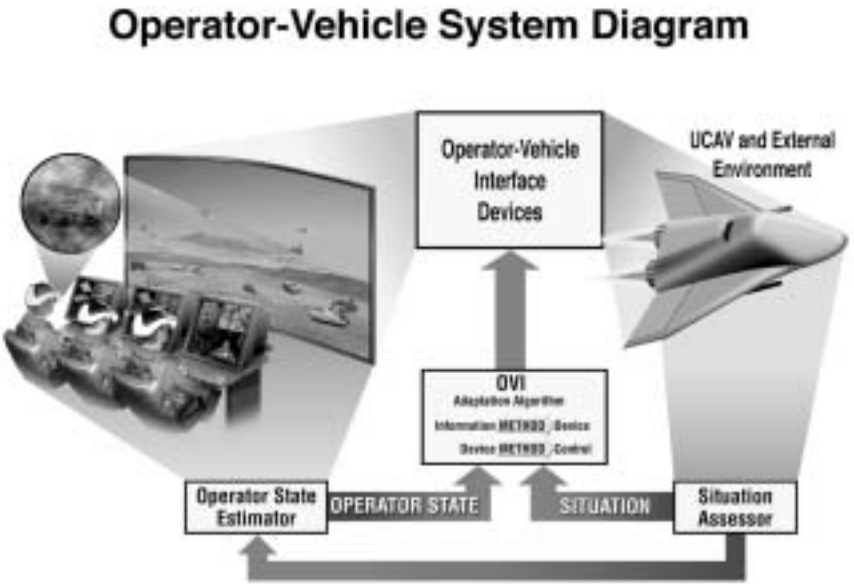

Figure 1.3: Adaptive UCAV system diagram.

Because of the vehicle's level of autonomy, it can perform many routine functions on its own. For example, the vehicle could reconfigure control surfaces if it sustained battle damage. It may also be able to autonomously adapt to certain mission events such as missile threats, thereby placing additional cognitive load on the operator to maintain adequate situation awareness if unexpected events occur. Since the operator's main function may be to intervene in these unanticipated events, cognitive work analysis is crucial if the success of the system is to be achieved (Vicente, 1995).

Would the operator be a pilot? This issue will always be debated, but if the UCAV is designed to be semiautonomous, i.e., preprogrammed to fly a route and avoid threats, but capable of accepting commands remotely, there will probably be little, if any, "hand flying" required. The operator of this air vehicle may not be a pilot and may control more than one vehicle at a time. The system diagram illustrating the entire control loop is shown in Figure 1.3.

Maybe a weapon systems officer would be a better operator? Maybe a targeting or intelligence specialist? However, no matter who the operators are they may have to adapt to changes in the mission capability of the vehicle by issuing additional control commands. These commands are not necessarily "stick and rudder" flight inputs, but rather can be added at a much higher level. For example, a voice command could be issued, such as "UCAV 2, target reassignment. Attack second priority target." These commands are at a much higher

level than just simple course corrections and could place a higher cognitive load on the operator.

One of the crucial aspects of this control loop shown in Figure 1.3 is the ability of *both* the vehicle and the operator to adapt. Not only can the operator adapt to changes in aircraft state, but by monitoring the operator state through physiological and other means such as behavioral task models, the EA contained in the ground-based software can assume tasks if the operator is cognitively overloaded. Since both the operator and the vehicle can adapt, cognitive systems engineering is especially crucial in this operator-vehicle system if we are to avoid cogminutia fragmentosa.

REFERENCES

Asimov, I. (1950). *I, robot.* New York: Fawcett.

Aviation Week & Space Technology. (1995, January 30). Automated cockpits: Who's in charge? *Aviation Week & Space Technology*, pp. 1–24.

Aviation Week & Space Technology. (1996, April 1). *Aviation Week & Space Technology.*

Billings, C. (1991). *Human centered automation* (NASA Tech Memo 103885). Moffett Field, CA: Ames Research Center.

Draper, C. S., Whitaker, H. P., & Young, L. R. (1964, September). The roles of men and instruments in control and guidance systems for spacecraft. In P*roceedings of the XVth International Astronautical Congress*, Warsaw, Poland.

Dornheim, M. (1999, October 18). Apache Tests Power of New Cockpit Tool. *Aviation Week and Space Technology*, 46–49.

Fuld, R. B. (1993, January). The fiction of function allocation. *Ergonomics in Design, 1*, 20–24.

Fulghum, D. (1996, February 5). Pilots to leave cockpit in future Air Force. *Aviation Week & Space Technology*, 26–28.

Gagne, R. M. (1962). *Psychological principles in systems development*. New York: Holt, Rinehart, & Winston.

Goodman, G. W., Jr. (1996, July). New eyes in the sky. *Armed Forces Journal International.*

Hancock, P. (1996, October). The future of function allocation. *Ergonomics in Design, 4*, 24–29.

Howell, W. C. (1993). Engineering psychology in a changing world. In L. W. Porter & M. R. Rosenzweig (Eds.), *Annual Review of Psychology* (pp. 231–263). Palo Alto, CA: Annual Reviews.

Klein, G. (1995). The value added by cognitive task analysis. In *Proceedings of the 39th Annual Meeting of the Human Factors Society* (pp. 530–533). Santa Monica, CA: HFS.

Knemeyer, S., & Yingling, G. L. (1966, November). Results of the USAF pilot factors program as they apply to flight safety. In *Proceedings of the 19th Annual International Air Safety Seminar,* Madrid, Spain.

Lizza, C., Rouse, D. , Small, R., & Zenyuh J. (1992, July). Pilot's Associate: An evolving philosophy. In T. Emerson, M. Reinecke, J. Reising, & R. Taylor (Eds.), *The Human-Electronic Crew: Is the Team Maturing* (Tech. Rep. WL–TR–92–3078). Wright-Patterson AFB, OH: Wright Laboratory.

McCall, G. H., & Corder, J. A. (1995). *New World Vistas, Air and Space Power for the 21st Century. Summary Volume.*

Miller, C., & Riley, V. (1995, December). Achieving the associate relationship; lessons learned from 10 years of research and design.. In J. Reising & R. Taylor (Eds.), *The Human-Electronic Crew : Can We Trust The Team?* (Tech. Rep. WL–TR–9–3039). Wright-Patterson AFB, OH: Wright Laboratory

Muir, B. M. (1987). Trust between humans and machines, and the design of decision aids. *International Journal of Man-Machine Studies, 27*, 527–539.

Raeth, P., & Reising, J. M, (1999). Transitioning basic research to build a dynamic model of pilot trust and workload allocation. *Mathematical and Computer Modeling, 30*, 49–165,

Riley, V. (1989). A general model of mixed-initiative human-machine systems. In *Proceedings of the 31st Annual Meeting of the Human Factors Society* (pp. 124–128). Santa Monica, CA: HFS.

Vicente, K. (1995). Task analysis, cognitive task analysis, cognitive work analysis: What's the difference? In *Proceedings of the 39th Annual Meeting of the Human Factors Society* (pp. 534–537). Santa Monica, CA: HFS.

Wickens, C.D. (1993). *Engineering psychology and human performance*. New York: Harper Collins.