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Cognitive engineering is the application of cognitive psychology and related disciplines to the design and operation of human-machine systems. Cognitive engineering combines both detailed and close study of the human worker in the actual work context and the study of the worker in more controlled environments. Cognitive engineering combines multiple methods and perspectives to achieve the goal of improved system performance. Given the origins of experimental psychology itself in issues regarding the design of human-machine systems, cognitive engineering is a core, or fundamental, discipline within academic psychology.

Cognitive Engineering is an applied cognitive science, or as Woods and Roth state Cognitive Engineering, "is an applied cognitive science that draws on the knowledge and techniques of cognitive psychology and related disciplines to provide the foundation for principle-driven design of person-machine systems" (Ref 1, p. 415). The focus is on the application of cognitive psychology to the design and construction of machines or human-machine systems.[2] While often described as the application of cognitive psychology in particular, most researchers in the field of Cognitive Engineering take an eclectic or ecumenical approach, borrowing from other disciplines as necessary, for example, anthropology and sociology. This interdisciplinary orientation enriches the methods available to cognitive engineers. Cognitive psychology, or applied experimental psychology, has strengths in the quantification of behaviour and experimental methods, but these can be supplemented with the qualitative and field methods developed by anthropologists and sociologists.[3]

Cognitive Engineering is also best regarded as a goal-directed activity. As Norman relates, "the goal of Cognitive Engineering is to come to understand the issues, to show how to make better choices when they exist, and to show what the tradeoffs are when, as is the usual case, an improvement in one domain leads to deficits in another" (Ref 2, p. 31). To accomplish this goal, cognitive engineers must first understand the human-machine system. This entails the need to become familiar with the specific work setting being examined, whether this is air-traffic control, battlefield management, medical monitoring, or, in historical settings, astronomical observation. The formal method of becoming familiar with the particular human-machine system often adapts the field methodology more familiar to anthropologists and sociologists than to experimental psychologists.[3] Indeed, the introduction of these field methods and a clear statement of the need to become highly familiar with the particulars of the human-machine work system is a marker of the *new* approach to cognitive engineering, which emerged in the late 20th century. Once the human-machine system is understood, improvements can be suggested using general principles of human cognition informed by domain-specific knowledge. These suggestions for system improvements are then subjected to rigorous tests to determine their efficacy, including their robustness in operational or close-to-operational (simulated) settings.

An outstanding issue is the relationship between Cognitive Engineering and Human Factors or Engineering Psychology. The latter two are terms that describe the application of human science and psychology to human-machine system design with the intent of improving system performance. However, while some advocates of Cognitive Engineering see the field as simply another dimension of the field of applied psychology or Human Factors (essentially Cognitive Engineering is completely continuous with psychology and Human Factors as a whole), another group see Cognitive Engineering as new and revolutionary. Although the former perspective is probably more historically accurate (as we outline in the next section of this review), the advocates of the *new* Cognitive Engineering have undoubtedly added important dimensions to the discipline and thereby expanded its scope. Nevertheless, the move towards the *new* Cognitive Engineering may have overlooked the field's historical legacy and continuing tradition in experimental laboratory research. As we will conclude, we suspect that Cognitive Engineering is simply a facet of Human Factors and fits comfortably within that discipline.

Although Cognitive Engineering might be regarded as a facet of Human Factors, one advantage of the introduction of the term is that it may have merits for rebranding Human Factors and cognitive psychology more broadly.[4] Indeed, adding the term *engineering* may have increased the professional recognition of Human Factors and cognitive psychology. This may add weight to the discipline, since engineering engenders a level of usefulness, practicality, and effectiveness. In the following review, we will provide a historical perspective on Cognitive Engineering, relay some of the contributions of the *new* approach to cognitive engineering, and the contributions of earlier approaches to cognitive engineering. Finally, we will conclude that Cognitive Engineering and, by extension, its capacity to effect improvements in the industrial landscape, is best achieved through a combination of both laboratory and field work.

PSYCHOLOGY HAS ALWAYS BEEN COGNITIVE ENGINEERING

Cognitive Engineering is not, despite pretensions,[1] an entirely novel idea and might be considered a natural aspect or facet of academic psychology. Indeed, much of psychology itself could be considered some form of cognitive engineering. Contemporary psychological text books, when presenting the history of psychology, often obscure its technological origins such that psychology appears less applied than it is in reality.[5] This was not the case in earlier psychology textbooks,[6] where the practical and applied origin of psychology was considerably more explicit. Academic psychology directly originated in a practical concern with optical technology: the personal equation in astronomy.

In the early nineteenth century, there was wide-spread recognition that astronomers differed in the times that they recorded transits. A transit in astronomy is when a celestial body crosses in front of a marker in either the eye-piece of a telescope or another celestial object. The individual differences in transit times were sufficient to have significant implications for important calculations needed for both navigation and geodesy. This would have wider societal implications for commerce and military operations, which were dependent on accurate geo-location. Wilhelm Wundt, Franciscus Donders, and the other founders of academic psychology were addressing the personal equation in their research.[7]

Until the introduction of photographic measurement methods in the late 19th century, which made earlier transit techniques obsolete, astronomers themselves were deeply concerned with the personal equation.[8] The chronoscope invented by Charles Wheatstone in the UK in the 1840s and the chronograph, developed by researchers in the United States, were developed to measure individuals' reaction times accurately and these technologies were quickly deployed to address the personal equation in astronomical observatories. Ormsby Mitchel, director of the Cincinnati College (now University of Cincinnati) Mt. Adams observatory, revolutionized the field by employing a galvanic barrel chronograph in astronomy. In 1851, with the help of colleagues such as Harvard astronomer Benjamin Peirce, Mitchel demonstrated to the American Association for the

Advancement of Science the level of precision that could be achieved by measuring and taking account of what Mitchel called *the personality of the eye*.[9] Inspired by Mitchel's pioneering work, George Airy[10] at the Greenwich observatory developed a series of transit studies using an artificial star. Airy would use this simulated task to measure an astronomer's personal equation or personality of the eye.

Observatories in the mid 19th century were comparatively well funded research organizations doing work important for society. The Greenwich observatory, for example, had a staff of 53 employees, including assistants and people hired to make computations (computers). The cognitive engineering undertaken by Airy and his contemporaries to more precisely control and improve observatory work revolutionized astronomical work and, as Schaffer[8] argues, resulted in the industrialization of the observatory. Indeed, this work industrialized science itself. As Mitchel (Ref 11, p. 176) wrote, "the observer himself is but an imperfect and variable machine, utterly incapable of marking the exact moments required." By studying the scientist, the scientist's cognitive system, and including this information in the system's design, the entire observatory system could be improved as a functional whole. The pioneers of psychology were cognitive engineers.

In pursuing the personal equation, Wundt was effectively undertaking a process analogous to contemporary approaches to cognitive engineering. He required highly trained participants for his perceptual research because this reflected the reality of workers in contemporary observatories. Boring reports in relation to Wundt's research that, "No observer who had performed less than 10,000 of these introspectively controlled reactions was suitable to provide data for published research from Wundt's laboratory" (Ref 12, p.172). Therefore, the origins of psychology as an academic field were a direct result of these early forays into what might be regarded as cognitive engineering. The astronomers of the time were highly trained and calibrated using for example, Mitchel's and Airy's techniques. Wundt's experimental participants were treated similarly, as they were replicates of their working models. Despite rumours to the contrary, the main thrust of

Wundt's laboratory work was ecologically realistic and reflected the working conditions of his intended audience.

In addition to the issue of the personal equation, other research topics explored by early academic psychologists also came directly from human-machine systems. These included the issue of range estimation. The rifled barrel was introduced to artillery in the 1840s. Rifling, which results in spinning the projectile, dramatically increased the range and accuracy of artillery fire. However, the benefits of rifling could only be realized if the gunner could accurately estimate the distance to the target. Herman von Helmholtz developed the first optical range finder, which used perceptual research to improve range estimation. Charles Wheatstone, inventor of the stereoscope and chronoscope, also explored optical issues regarding distance estimation, and also worked for the British admiralty to improve gunners' rate of fire, clearly an early forerunner of contemporary human-machine system research.[13,14]

Given Helmholtz's practical interest in range estimation, it is hardly surprising that his protégé Wundt continued his work on range estimation and human-machine system research. Indeed, the majority of Wundt's empirical research was in visual space perception.[15] Of what practical use is knowing where things are in space from visual cues alone? Simply, you would have only needed to ask a naval gunner of the era. The emergence of academic psychology is no coincidence, but fit the revolution in technology of the time. In effect, psychology was the era's attempt at cognitive engineering.[16] There have always been concerns regarding the ecological validity of psychological laboratory research and this is not new.[5,17]

THE NEW COGNITIVE ENGINEERING

This section details three frameworks within Cognitive Engineering that are often considered to be more recent or 'newer' additions. The first is Cognitive Systems Engineering (CSE), an approach which emphasises the study of macro-cognition, or the cognition of skilled operators working in actual socio-technical systems. This is distinguished from the study of micro-cognition which often focuses on the sub-components of cognition of individuals'. Macro-cognitive constructs are generally broad in nature (e.g., mental simulation, situational awareness) while micro-cognitive constructs are narrower in focus (e.g., sustained attention, working memory). As depicted in Figure 1, the distinction between macro- and micro-cognition is an ontological distinction, with micro-cognition focusing on the sub-components of cognition considered in isolation and macro-cognition examining the emergent properties that become evident when the human cognitive system is situated in a larger system made up of both other people (socio-) and tools (technical-). This distinction is unique, though correlated, with the choice of epistemological method, experimentation versus observation. While advocates of CSE may be found more often in quadrant B, performing observational research on macro-cognition, and cognitive psychologists in quadrant C, performing controlled laboratory studies of micro-cognition, research in quadrants A and D is important and should not be neglected. The second framework is Naturalistic Decision Making (NDM), which also concerns macro-cognition. The third is Ecological Interface Design (EID) which focuses on the affordances which the work domain offers the human operator. All three share in common an approach that focuses heavily on the interplay of socio-technical systems. Some, however, consider NDM and EID to be frameworks within CSE itself. All focus more on fieldwork than laboratory work, perhaps, distinguishing the new CE from the more traditional approach to CE; researchers in the newer approaches of CSE and NDM tend to be found in quadrant B (but not exclusively).

Klein et al.[18] suggest that a focus on macro-cognition in CSE and NDM is beneficial, since it allows an assessment of human performance in context. Context is critical to understanding system performance. For example, if workers were denied access to the prosthetics they use to do their jobs in the actual work environment (for example, calculators or physical reminders for a task requiring memory, like post-it notes) their behaviour is unlikely to have relevance to understanding how the system works in practice. Macro-cognition also requires a different approach than the study of micro-cognition, although it might be argued that micro-cognition may benefit by being contextualized by macro-cognition studies. The overall perspective of these approaches is that studying the person in the actual working system is radically different from studying the person in isolation of the entire working system.[19]

Cognitive Systems Engineering

Defining Cognitive Systems Engineering (CSE) is difficult since the term is sometimes used interchangeably with cognitive engineering. Militello, Dominguez, Lintern, & Klein (Ref 20, p.3) contend that "CSE is an approach to the design of technology, training, and processes intended to manage cognitive complexity in socio-technical systems." It is also referred to as *joint cognitive systems*. At a basic level, a socio-technical system describes the interaction between people and technology, bearing in mind that the term technology can refer to not only machinery but procedures and knowledge as well.[21] Further, it is one in which humans provide essential functionality related to deciding, planning for, collaborating with, and managing the system.

CSE originated around the time that human-machine interaction grew so complex that these two components, human and machine, were better viewed as a single all-encompassing system.[22] By emphasising macro-cognitive processes over micro-cognitive processes, CSE attempts to explain the *what* and the *why* in terms of the joint cognitive system, in addition to the *how*.[23] The core values and intentions of CSE include: (1) observation, where practitioners observe work being done to understand how workers do what they do and adapt within their environment; (2) abstraction, which involves retrieving information and patterns from the various situations and settings; and (3) discovery and innovation, whereby the information garnered from the first two processes is utilised to create improved concepts and procedures.[24] In CSE, there is no standardised process or sequence of design. Rather, practitioners are constantly re-evaluating the design of the system as they proceed. Any changes that are made to any aspect of the socio-technical system will likely have carry-over effects on other aspects of the system and this creates an iterative loop. This iterative re-evaluation is integral to the approach, and highlights the creative and opportunistic process of CSE.[20]

An important advantage of CSE over alternative approaches is that, conceptually, it takes into account attributes of the particular environment of a system.[25] This is often crucial, as the environment can have a significant bearing on the functionality of the system as well as the desired or required output. For instance, compare a large group of networked computers in a public library with a similar group in a police department. The police department and public library have radically different requirements, for example, regarding security of data and access. There is a concern, perhaps unwarranted, that CSE is a move away from rigorous systematic methods to one more emulative of haphazard tinkering. In the drive to examine and improve complete or intact work systems, there may be a tendency to overlook the merits of isolating system components and rigorously undertaking tests by controlling relevant variables (e.g., the experimental method).

There are many examples of CSE improving socio-technical systems.[26, 27] Recently, it was used to radically improve landmine detection rates from 5% to 95% within the U.S. Army. The first step here was to observe soldiers who were considered experts in detecting landmines, as demonstrated by their superior detection rates. Information processing analyses were performed to extract the knowledge and skills they were utilising during detections, and afterwards cognitive models were developed using this information. These models were employed subsequently to guide the design of new training programs.[28] A similar approach was used to develop weather-related training initiatives for pilots. Cognitive interviews were conducted with expert general aviation pilots and cues were identified that could be associated with deteriorating weather conditions. These cues were incorporated into a computer-based training package, the introduction of which was associated with improvements in pilots' capacity to detect deteriorating weather conditions during simulated flight.[29]

There are also numerous cases where designers have failed to include CSE in the design process, leading to poor results. A well-known Los Angeles medical centre was forced to withdraw highly-anticipated new computer software following user complaints,[30] and a $170 million FBI computer system suffered a similar fate following a lack of CSE during design and implementation. In the case of the FBI computer system, failures arose because it did not offer the agents many of the functions they required. This was said to be because the agency failed to define their operational processes beforehand, leaving the software developers to do this instead.[31] Despite the opportunities afforded by CSE in improving human performance, it faces some challenges in becoming better accepted by the design and engineering communities. One barrier is the complex terminology used by CSE practitioners, and the fact that there is often more than one term used to describe the same construct. This makes it difficult for practitioners outside the CSE field to understand the role of cognitive engineering.[20] Secondly, it has yet to outwardly establish itself to other members of design disciplines. Often, CSE advocates confront difficulties in quantifying gains precipitated by the CSE approach. If both the methods and the terminology of CSE can evolve into forms which are more comprehensible for people in neighbouring disciplines such as engineering, these disciplines may gradually begin to incorporate the use of CSE during the design process.[20]

Naturalistic Decision Making

Naturalistic decision making (NDM) can be defined as “how people make decisions in real-world settings,” (Ref 32, p.456). This is one of the similarities that NDM shares with CSE, since it focuses on macro-cognition, rather than micro-cognition. As its name implies, NDM was originally based around decision making in naturalistic contexts. In the past decade, however, it has evolved to include a focus on cognitive constructs within these contexts, also known as macro-cognition.[33] Considerable evidence exists to indicate that decision-making within ideal conditions is not always representative of the decision-making strategies that are engaged in practice.[34] This is unsurprising since both utility theory and behavioural decision theory propose that decisions, optimally, should be made in a step-by-step manner, with alternative actions and potential outcomes compared via a deliberate and calculated approach. This is time-consuming and, in natural settings, decision makers are forced to take cognitive short-cuts or use heuristics.

NDM advocates assert that decision making strategies that are engaged in field settings are often distinct from the strategies that are evident in isolated or in relatively impoverished laboratory environments. While traditional research describes optimal decision making with normative models such as utility theory, other models such as the *recognition-primed decision (RPD)* model are thought by NDM advocates to better express how decisions are made in naturalistic settings.

The RPD model emerged from work by Klein and associates,[35] who undertook cognitive task analyses with fire fighters. They noted that the fire fighters were not engaging decision strategies consistent with traditional models, such as behavioural decision theory and utility theory. This was especially the case in situations that were time-pressured and/or that embodied uncertain or ill-defined goals.[36] It is difficult to imagine a fire fighter pausing amid putting out a burning house with people trapped inside, to carefully sort through and compare options mentally. While this may increase the likelihood that the fire fighter will select the optimal response (although it may not), it will definitely consume a large portion of time and cognitive resources. When making decisions in the field, experts in particular, use pattern recognition techniques to match a situation with potential responses to that situation. For example, on glancing at the burning house and seeing a particular type or colour of smoke, the expert fire fighter can rapidly identify the type of combustion and its implications in responding to the fire. This could be a result of matching the features of the event being experienced to a previous event involving a similar-style house. This approach often yields a much shorter decision making duration, and frequently, the first option considered is the 'right' option under the circumstances.[37] Studies of chess players several decades ago showed that the performance of expert players was barely affected by a considerable shortening of the time permitted to make moves, while the performance of non-experts suffered markedly. Furthermore, the very first options considered by experienced players at each move were much more likely to be considered adequate than the first options considered by non-experts.[38] The early studies by Klein and colleagues also established that experts were using a tactic – which had been identified over thirty years previously – referred to as satisficing.[39] This describes the act of choosing the first feasible option that comes to mind (satisficing), rather than searching for the optimal option (optimizing). When contemplating an option, experts would often 'play it out' as a mental simulation to get a better sense of the suitability of the decision. If it was considered inappropriate, they would make slight alterations or consider an alternative option. If it 'played out' successfully, the option would be implemented.[32]

NDM has made some important contributions to understanding how experts operate in naturalistic settings by addressing a number of areas previously neglected in psychological research and by introducing new models and methods of psychological inquiry. It is also responsible for attracting applied investigators into the field of Cognitive Engineering. NDM has attractive appeal given the focus on high-profile individuals (experts) in actual work environments. One challenge, however, is that the proponents of NDM frequently highlight the applied nature of their methodologies. For example, Endsley et al. (Ref 25, p. 3) relates that "NDM specifically seeks to provide rich descriptions of how people make decisions in the real world…" The emphasis on 'real-world' and 'real-life' settings is a recurring theme within the NDM literature. However, as Rogers[40] suggests, these terms carry little meaning and may allow authors to avoid being specific or avoid developing theoretical perspectives that can be generalised and tested (see also Ref 41). Of course, rich description is terminology borrowed from ethnology and other disciplines using sophisticated qualitative methodologies. Aside from the issue of qualitative methods putting NDM at odds with those advocating quantitative methods for Cognitive Engineering, it may overlook the long tradition of cultural analysis and qualitative methods used in psychology which can trace its origins to the emergence of the discipline. Regardless, NDM should be applauded for its contribution to the field by more forcefully advocating rigorous qualitative data analysis, a tool that has been somewhat neglected by psychologists and thus, by researchers in human factors.

Ecological Interface Design

Ecological interface design (EID) differs from CSE and NDM insofar as it places particular emphasis not on the *task* within the work domain but on the affordances which the *work domain* itself offers the operator.[25] It bears a close resemblance to cognitive work analysis. An ecological approach within human factors or applied psychology is not new and could historically be traced from James Gibson back via Edward Tolman, Edwin Holt and Hugo Munsterberg to William James and Wilhem Wundt. However, EID has a more narrow scope and focuses “on the specific problem of how to design human-computer interfaces for complex socio-technical systems” (Ref 42, p. 63).

The main aim of ecological interface design (EID) is to devise systems that support operator *adaptation*. It is not possible for designers to anticipate every single situation that may arise, and therefore, there is always a possibility that unexpected, non-routine events can take place.[43,44] Unanticipated events such as these range from the mundane and frequently occurring, to the extremely rare and catastrophic. The latter often take operators by surprise and the subsequent outcomes can be devastating.[45] Through the appropriate application of EID techniques in the design process, operators should be able to cope better when faced with these events. The approach is based on the principles that attempting to completely eliminate errors is futile, but instead, efforts should be directed towards their control and management. The primary focus here is on errors of ‘intention,’ which are distinguishable from errors of ‘execution.’ The former can be conceptualised as mistakes while the latter can be thought of as slips. Unanticipated events are plagued by mistakes more so than slips, while the opposite is true for routine events. While other methodologies within Cognitive Engineering can be employed to help prevent slips, EID, according to its proponents, is the method most able to effectively reduce mistakes.[44] Often, these types of errors, although rare, can lead to the most severe outcomes.[46] EID is designed to provide the operator with the greatest likelihood of successfully negotiating these types of errors when they occur, by facilitating adaptation.[42] It is thought that the partial meltdown of a nuclear power plant in the United States, known as the Three Mile Island disaster, would have been avoided had elements of EID been incorporated into the control room design. After the occurrence of an unexpected sequence of events, insufficient warning information displayed on the control room interface led to operators making mistakes which in turn led to the subsequent catastrophe.[47]

Two key aspects of EID are 1) abstraction hierarchies, and 2) the skills, rules, and knowledge taxonomy. An abstraction hierarchy is used to describe constraints within an environment in such a way that it aids potential coping methods.[44] Information in an abstraction hierarchy can be divided into lower level or higher level information, with the former describing physical information and the latter describing functional information. Complementing this is the use of the skills, rules, and knowledge taxonomy to elucidate the cognitive processes involved in decision making in these settings. Skill-based behaviour concerns direct behavioural interaction with the environment. Rule-based behaviour concerns perceptual information and cues. Knowledge-based behaviour involves more deliberate problem solving behaviour, and demands more effort than either skill-based or rule-based behaviour.[42]

There are examples of the implementation of EID leading to improved performance over previously state-of-the-art methods in socio-technical systems.[48,49] These improvements tend to be limited to tasks of a more complex nature, although there are no losses in performance following its application to simpler tasks too.[44] As to the impetus of these gains, there are several likely contributions. These include the presentation of information in forms (usually visual) that enable the categorisation of information, the anticipation of changes that are likely to occur, and the consequences of intended actions.

Nevertheless, it must be noted that the positive effects generated by EID do not occur with all people as evident in individual differences.[44] Furthermore, the vast majority of the EID work appears to be contained to visual aspects of design, as related by Watson & Sanderson,[50] who emphasise that EID can be useful when involving modalities other than just visual perception. Another issue is the amount (or lack) of empirical validation of the success stories. There is, however, some research demonstrating that EID has led to improved visual performance in a simulation of a power plant.[51,52]

TRADITIONAL COGNITIVE ENGINEERING

This section comprises three research topics within Cognitive Engineering which might be considered to represent the more traditional approach to cognitive engineering.[53] The three topics are vigilance, skill learning/expertise, and visual displays and iconic cues. These topics make extensive use of what new cognitive engineering advocates would call micro-cognition and experimentation, especially in controlled laboratory settings (in Figure 1, quadrant C). These approaches are micro-cognitive in orientation because researchers in these traditions do appear to take a reductive orientation and attempt to isolate cognitive sub-components. Our hope in highlighting these topics is to demonstrate the complementary nature of laboratory research or traditional human factors with the concerns and techniques being developed by the new Cognitive Engineering. Both approaches can be integrated effectively and the field, to be effective, needs to cover all quadrants in Figure 1. At the very least, the examples highlight the continued relevance of tightly controlled laboratory study to Cognitive Engineering.

Vigilance

Increasingly, modern work environments are dependent upon automated systems. This is especially the case in critical infrastructure or industries requiring high reliability, including industrial manufacturing, utility system management, aviation, ground transportation, defence systems, and medicine. Automation has developed rapidly in response to the demands of higher labour costs and the desire for improved precision.[54] Nevertheless, automated systems remain dependent upon human operators to monitor the integrity of the system and intervene when necessary to either prevent a system failure or to ensure that the system is operating optimally.[55,56] The need for operator intervention is unpredictable in both its frequency and its intensity in automated systems, thereby relegating the operator to the role of a passive observer.[57,58]

The difficulty with this role is the need to maintain sufficient attention to the task, despite a relatively passive role for the human monitor. This monitoring for rarely occurring system changes is labelled vigilance. Systematic research on vigilance began with the work of Norman Mackworth,[59,60] who was requested to work on a practical problem encountered by the Royal Air Force (United Kingdom) during the Second World War. At the time, pulse-position radio detection and ranging – radar – was a new technological innovation employed to discover the presence of surfaced Axis submarines. The diesel submarines of the era would have to surface to recharge their batteries. When they surfaced they would create a radar signature that could be detected by an airborne-based system. Undoubtedly, airborne radar reconnaissance was an improvement over earlier techniques employed to detect U-boats, such as training sea gulls to flock around them.[61] However, the system had a serious problem. Regardless of their high level of motivation and extensive training, the airborne observers began to miss 'blips' on their radar scopes indicating the presence of submarines after only 30 min of watch. Losses in vigilance, if left unchecked, could result in increasing losses of Allied vessels to submarine attacks. From Mackworth's early research onwards, the primary interest of vigilance researchers has been the decline in performance over time-on-task, or the vigilance decrement. The vigilance decrement is marked by either a decline in signal detections with time-on-task or an increase in response latencies with time-on-task.

The intriguing aspect of the vigilance decrement is that the loss of performance occurs even though critical signals are perceptible when observers are forewarned about them (e.g., it is not that the targets are impossible to detect in an alerted state). Vigilance tasks require the detection of perceptible changes that are not compelling changes in the operating environment. These target or critical stimuli appear unpredictably with a relatively low probability of occurrence and the observer has no control over when they appear.[62,63,64,65,66,67,68] The long history of studies conducted since Mackworth's seminal investigations provide a convincing case that the central nervous system, regardless of species (the exception may be dolphins, see Helton et al.[69] for discussion), cannot sustain attention for an indefinite period of time and thus, that the focus of attention is temporally limited. Dukas and Clark[70] propose that the vigilance decrement is a dominant factor determining animal behaviour, including human operator behaviour. The decrement can result in failures to respond accurately to a change in the system state or a failure to respond in sufficient time to prevent a system failure.[71] The use of automated systems in a broader context can result in other concerns as well, including a loss of skills, a lack of work identity, increases in stress and fatigue, and in some cases, violations of standard operating procedures.[72]

Researchers of vigilance examine the underlying factors influencing the decrement. An understanding of these relevant factors may help system designers develop better systems to maintain operator vigilance. If this, however, remains elusive, cognitive engineers have also examined whether there are indicators of the operator being in an unvigilant state. These indicators can then be used to 'monitor the monitor', in an approach called augmented cognition. Augmented Cognition is a recently developed field of research seeking to extend the information processing capacities of human operators by using real-time assessments of human cognitive states and employing these real-time assessments as inputs in the technological system.[73] The human operator's cognitive state can be assessed with a variety of sensor technologies detecting behavioural, psychophysiological and neurophysiological data acquired from the operator in real time. These data can then be used to adapt or augment the technological interface to significantly improve human performance. Augmented Cognition techniques may enable organisations to predict or detect when operators will be likely to miss target stimuli. Detecting these operator changes may lead to a dramatic reduction in accidents-mishaps, by both increasing awareness as to when these errors are more likely to occur, and perhaps, in the future by altering the system itself.

Peripheral and central physiological markers can also be used to gauge the amount of cognitive resources that a human operator is expending. For example, pupil diameter when controlling for lighting may be a marker of cognitive resource expenditure.[74,75] Self-reported task engagement has also been found to be negatively correlated with blink rate while self-reported distress is positively correlated with heart rate.[76,77] Several studies have shown that there is a close relation between mental activity and cerebral blood flow.[78,79] Recent signal detection studies[80,81,82] indicate that the temporal decline in target detections that typifies vigilance performance, the vigilance decrement, is accompanied by a parallel decline in cerebral blood flow. They also indicate that the absolute level of cerebral blood flow in vigilance tasks is positively related to the psychophysical and cognitive demands placed upon observers and that these effects are lateralized to the right cerebral hemisphere.[80,82,83]

The future of vigilance research will take a neuro-ergonomic perspective in an attempt to prevent vigilance decrement via system intervention when the human operator is in an unvigilant state. Cognitive Engineering will see the benefits of neuroscience by absorbing both the findings and techniques coming from the neurosciences. These cognitive-neuro systems will revolutionize the way people interact with machines. If integrated with the newer perspective of CSE, it suggests that the introduction of physiological monitoring systems will themselves come to be used by operators to improve system performance. This will itself require further investigation.

Skill Learning and Expertise

Researchers propose a developmental transition in skill from active control to automaticity.[84,85,86,87] The automatization of skill frees up attention for other concurrent tasks and operations. Changes in attention during skill development are well established.[86,87] Fitts' and Posner's[88] and Andersons's[89] stage models of expertise development are cases in point. In these models, the initial cognitive-stage, requiring active control, consists of close attention to cues and feedback. Performance during the cognitive-stage is not fluid and requires the coordination of the separate skill elements by the individual. Skill production during this stage is attention demanding and places limits on performing other activities. The next associative-stage in the model consists of organizing these separate skill elements into larger units or chunks by chaining operations and procedures together. This organization results in an increase in production fluidity-speed and a decrease in attention requirements. The final autonomous-stage consists of the skill becoming relatively independent from active cognitive control and attention, or in other words, automatic. This enables an even greater freeing up of attention.

A common example is driving an automobile. A well-trained driver is usually able to drive (primary task) while simultaneously engaging in a conversation with a passenger (secondary task). When driving conditions, however, become more difficult, such as during dense, unpredictable traffic, or on slippery roads, the conversation needs to stop since the attention resources needed to undertake both tasks simultaneously is limited. These attention resources represent anything of limited supply in the control system of the individual: glucose-oxygen, neurotransmitters, neurons, or actual neuronal groups. The skill level of the operator also determines this attention trade-off between the primary task of driving and the secondary task of carrying on a conversation. A novice will need to stop talking even sooner than an expert.

A skill performed without attention costs is considered to be automatic.[86] Automaticity is itself gradated so that tasks require more or less attention resources. Some researchers argue that all tasks have some attention costs, although they can be small, to the point that it is difficult to determine the attention cost with current methods[90] (see Ref 91 for an alternative perspective). Nevertheless, there is significant evidence to suggest that skills become more automated and less attention demanding with practice.[92] Skill execution in the early stage of learning requires the executive attention system to actively integrate sub-components of the skill and coordinate their production.[87] The attention demands of skill production are less intense with practice, because the sub-routines have been stored in larger memory units or chunks[93] and the brain has reorganized to be more efficient.[94,95]

Implicit learning studies have shown that contextual regularities that affect performance can be acquired independent of conscious awareness.[96] In these implicit learning studies the human participant must actively attend to the display for the sequences to be learned.[97] Participants may be unaware of having learned a particular sequence, they are, however, certainly aware of the original perceptual inputs. They are not learning subliminally. There is research showing that later visual performance can be influenced by prior exposure to subliminal stimuli.[98] However, in these subliminal perceptual learning experiments, the learning only occurs when the subliminal information is presented concurrently with actively attended to stimuli. Apparently, mere exposure is not sufficient to initiate learning.[99] The learning of complex skills, at least, appears to require attention or the investment of attention. Especially in the novice stage, performance can be disrupted by other tasks placing demands on attention. Later, as the skill becomes more automatic, attention can be redirected to other objects or tasks. Although it is certainly possible that learning can occur without any input from executive attention, there is very little evidence to support this contention, especially in the acquisition of complex skills. Understanding the role of attention in skill learning can result in improvements in instructional design or training systems, for example, Cognitive Load Theory.[100] This perspective is also informative for making adaptive user interfaces that can scale to the individual's skill level, e.g. the system could scale to a novice and provide more attention support.

One challenge for research involving the acquisition of complex skills is determining who is actually highly skilled, or expert, at the task (this is also a problem for NDM). While one could rely on professional reputation, often this can be due to seniority or presentation ability, and not actual level of skill. This is where using the laboratory methods developed by skill researchers has additional merits over merely observing individuals in the field (e.g., doing work ethnology). If the skill is not obvious without objective standards of the level of ability, techniques developed in the laboratory can be employed to reveal relative skill level. Many occupational skills are not like track-and-field events with objective performance metrics (time or distance) that are obvious to all. Instead, complex skills require integrative diagnosis. The later is difficult to establish. Researchers have developed methods, however, to resolve this challenge. EXPERTise, for example, is a psychometric tool that is designed to distinguish expert from competent and novice practitioners.[101,102] EXPERTise is specifically designed to assess diagnostic expertise when using human-machine interfaces. Performance is assessed on a series of five tasks, each of which incorporates domain-relevant stimuli (derived from cognitive interviews of subject-matter experts) and capitalises on operators' capacity for cue utilisation. The utility of EXPERTise lies in its use of norms in preference to assessments of performance against a standard. Recent analyses have yielded a test-retest reliability of 0.79 and 0.78 at six monthly intervals.[103] In relation to predictive validity, statistically significant relationships have been established between performance-based classifications on EXPERTise, and accuracy on high fidelity diagnostic assessment tasks in the context of power controllers[104] and paediatricians.[105]

Displays and Iconic Cues

Although Human Factors has a long history of research into the appropriate display of information,[106] current work in the area integrates findings from laboratory studies with more naturalistic examinations of skilled operators (similar to NDM). In modern automated work systems, operators will often be relatively disengaged from the system when a system alert is issued (see also the section on vigilance above). From an information processing perspective, disengagement from a primary task inevitably results in a situation where the acquisition, integration, and interpretation of information associated with a change in the system state must be completed within a shorter period of time than might be the case if the operator was fully engaged in system operation. Where primary, task-related information is sampled on a continuous basis and an existing schema or mental model is updated, the information can be prioritized so that a relatively limited number of key indicators or cues are retained, thereby reducing the demands on working memory.[102] However, where a system-related problem occurs in the absence of regular sampling, the process of information acquisition is necessarily broad initially in an attempt to identify the patterns of cues that are evident, and thereby develop an accurate diagnosis.[107]

For more experienced operators, the process of information acquisition will quickly become more refined to a point where the pattern is recognised and the diagnosis is resolved. Researchers, for example, conducted a series of experiments in which they were able to identify the key features that competent pilots engage during a partial engine failure in a simulated aircraft.[108] However, for less experienced operators, the process of information acquisition is considerably less structured and requires a level of time and resources beyond that required by experts.[109] The difficulty for the less experienced operator lies in an inability to quickly recognise and integrate cues to quickly draw meaning from a situation. Helton and colleagues[110] have shown that the workload imposed by these demands is a significant source of distress for operators that further impacts operator performance.[111,112] To cope with these demands, the process of information acquisition tends to involve the search for specific information that will point towards a specific cause, and might thus explain the change in the system state. Overall, it is a process that is time and resource intensive, emotionally distressing, and is subject to error.[113]

Iconic cues are tools, however, that have the capacity to highlight a change in the system state, direct the attention of the operator to key features that will enable a more rapid and a more accurate diagnosis and response to the change in the system state. Cues represent feature-event relationships in memory and they are used to interpret situations rapidly and with relatively little demand on working memory resources.[17,107] At a fundamental level, there are particular features that hold some meaning to the operator by virtue of their association with specific events in memory and it is this association that provides the basis for the cue. Where a feature-event relation becomes more familiar, exposure to even a relatively limited portrayal of this feature can trigger a non-conscious association in memory.

The application of visual cues is evident in a wide range of environments, including weather decision-making by pilots,[29] the interpretation of murder scenes by forensic investigators,[114] the identification of an appropriate point of entry to a building by fire fighters,[115] and the management of convulsions in an infant by paediatricians.[116] In each case, expert practitioners engage a relatively limited number of specific features to interpret a situation. However, the cues can be taught to competent practitioners with resultant improvements in performance.[117]

The use of icons as cues is common in a range of industrial environments, including aviation and medicine.[115] For example, in the medical context physicians will draw conclusions on the basis of visual representations of heart rate. Similarly, in aviation, icons are used to display the trajectory of the aircraft along an optimal descent path. In both cases, responses are expected if the icons depict a deviation from the normal limits. Given the importance of cues for system diagnosis, display designers can create better displays which enhance the recognition of icons. For example, highlighting features or increasing their salience in the display. The techniques used to enhance icon recognition would employ all the results of laboratory studies looking at visual search. This approach integrates the work of traditional psychology or Human Factors laboratories with the newer approach of NDM and suggests a bridge between the two Cognitive Engineering camps.

CONCLUSION

This review of both the new and traditional approaches to Cognitive Engineering was intended to highlight their complementary nature. Advocates of the new approaches are correct to point out that any over-emphasis on micro-cognition without research of macro-cognition can be harmful to cognitive engineering. Context is important. Neglecting research of micro-cognition is, however, potentially self-defeating. For example, some engineers, including cognitive engineers, might suggest that the issue of vigilance can be designed out of the system or does not occur in operational settings (despite numerous studies showing otherwise, see Ref 118). For example, colleagues in a North American defence laboratory recently indicated concerns to one of the authors that some members of a policy advisory board had indicated that vigilance was no longer a serious concern in unmanned systems. This view, however, directly contradicts the findings of a recent review of human factors issues in unmanned operations conducted by Defence Research and Development Canada. Arrabito et al. (Ref 119, p.3) state that "In contrast, for UVs [unmanned vehicles] that are highly automated (e.g., automated take-off and landing, and pre-programmed flight), the human factors issues are primarily related to problems in operator supervisory control such as maintaining vigilance." Future uninhabited vehicles will be highly automated, and reviews by allied defence forces conclude that maintaining operator vigilance is the critical issue in future uninhabited vehicle operations. While innovations in designs can result in improvements in overall system performance, the problem of maintaining human operator vigilance is not going to subside. Complete automation without human supervision is fantasy. Design will, furthermore, not mitigate the effects of losses of human vigilance. In reality, increases in system automation will likely exacerbate the issue.[64] This concern is also echoed in other industries where increasing automation has changed the nature of human work from active participation to system monitoring.[118] Research on vigilance has a relatively long history, but this does not merit dismissing its relevance. Well conducted micro-cognitive research (in Figure 1, quadrant C) is more likely to lead to successful counter-measures in this case.

Another issue which may be resolved is the metaphorical distance between laboratory and natural settings, which is often confused with the epistemological method distinction noted in Figure 1. Zsambok & Klein[120] list eight key contextual factors which constitute NDM situations, including a requirement for environments to be "uncertain and dynamic (not static, simulated environments)" (Zsambok & Klein, Ref 120, p.5). Many simulated environments, however, can be recognised as both uncertain and dynamic. Indeed, the separation between a simulated and 'real' environment will erode increasingly. As work becomes more like a simulation (for example, uninhabited vehicle operations) and simulations become more like work, eventually the laboratory and the real world will integrate. The distinction between the 'real' world and the laboratory may be a bit overplayed. Research in both environments is likely to be complementary.

The new and traditional conceptualizations of cognitive engineering should merge, since both provide important contributions to the overall field. While one of the beliefs of a free market is that competition results in better products, we have to wonder how much energy is being wasted on marketing the various brands of Cognitive Engineering and whether this could, in the long run, be damaging Cognitive Engineering as a discipline. The field, for example, does not need to constantly add esoteric terminology. Otherwise, Cognitive Engineering will become as hard to comprehend as a post-modern novel. Advocates of the new approaches need to recognize that while they are offering some new ideas, they are actually not necessarily a radical break with traditional human factors or applied psychology. Many engineers are sceptical of psychology however it is repackaged. Instead of fixating on terminology and branding, the key may be to focus on results. For example, how many introductory psychology textbooks include sections on Fitts' Law,[121] Hicks Law, Stimulus-Response compatibility, etc.? All are substantial and significant contributions of psychology to real world human-machine interfaces. For that matter, even psychophysics is slowly being edged out of the introductory courses to the field, despite being the origin of the field and still immensely useful.

Perhaps, the lack of consistency and recognition of success is hampering the field of psychology and its sub-fields like Cognitive Engineering. Essentially, psychology has always been Cognitive Engineering.[5]

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