Connecting design with cognition at work

Chapter · December 2008

DOI: 10.1016/B978-008045089-6.50010-1

2 authors:

David D Woods
The Ohio State University

Axel Roesler
University of Washington Seattle

7

CONNECTING DESIGN WITH COGNITION AT WORK

DAVID WOODS
The Ohio State University, OH, USA

AXEL ROESLER
University of Washington, Seattle, WA, USA

1. INTRODUCTION

> In design, we either hobble or support people's natural ability to express forms of expertise. There is no neutral. (Woods, 2002)

What is the relationship between design and cognition? This question is especially important because new technological capabilities have been appearing at an accelerating rate. First, technologies for more autonomous machines create the image of future machines that do things as substitutes for our own activities, or that even become alternatives to us (Kiesler and Hinds, 2004). Second, the technology for connecting people at a distance provides new opportunities to coordinate activity across large distances and to integrate activities that go on at different places or at differing time scales (Hinds and Kiesler, 2002). Third, the technology of collecting, sorting, and focusing data has grow so rapidly that people have available to them hyper-massive fields of data for analyzing situations and generating new or revised plans of action (Woods et al., 2002; Thomas and Cook, 2005). Fourth, there are new ways to visualize data sets, to fuse feeds from different sensor types, to look at aspects of the world as if we were standing in places that are difficult, expensive, dangerous or impossible to stand in. Sensors connect us and project us into remote situations where we can assume and change different points of observation. All of these vectors of technological change have profound implications for what people do, why they want to do these things, and how they will do these activities in the future. How can designers use the new powers to accelerate human skill acquisition and amplify human performance?

What is the relationship between cognition and design? One longstanding perspective on this relationship is that people have severe limits on their memory, attention and problem solving capabilities. People are prone to illusions and biases of many kinds (Gilovich et al., 2002; Kahneman and Tversky, 1996; but see Gigerenzer, 2000; Zsambok and Klein, 1997). In this view, design then would use new technological capabilities to develop prostheses that overcome the inherent weaknesses of people. For example, some people want to design machines that watch over people in action to see how badly their limitations may be impacting their performance (e.g. Schmorrow, 2005). Depending on the machine's assessment of how people's mental or physical state is changing, the machine will decide when and how to change the interface and change user tasks so that the demands remain within people's limited capabilities.

But equally longstanding is a completely different perspective about cognition and the impact of design. People are active, adaptive, goal seeking agents who re-design objects through their activities so that devices work for them (Winograd and Flores, 1986; Flach and Hoffman, 2003; Woods and Hollnagel, 2006). This view starts with people as meaning seeking, explanation generating, attention focusing, learning agents (Bruner, 1990; Weick, 1995). Actually, people, when acting expertly, are a model of competent action, and often the only model of competence available to study when one wants to understand how these processes of cognition work (see Feltovich et al., 1997; Ericsson et al., 2006; Roesler and Woods, in Chapter 8 of this volume). People will learn to express various [AU1] forms of expertise with experience, and they will shape the artifacts they encounter and interact with as resources to cope with the demands of the situations they face as they seek to meet their goals. Designed artifacts and systems then are resources that stimulate people to adapt to achieve their purposes – triggering adaptive behavior that expands what people can achieve (Woods and Dekker, 2000; Woods et al., 2004).

These expansive adaptations are not simply good or bad. Rather they transform systems leading to new roles, new ways of doing things, new reasons to do things. Technology change and new designs are one set of drivers in these processes of organizational transformation and human adaptation. The changes that are triggered result in new levels of performance on some dimensions, new squeezes on performance in other places, new side effects when things that were separate become connected, and new forms of complexity. The basic dynamic is captured in the Law of Stretched Systems (Woods, 2002; Woods and Hollnagel, 2006).

> *The Law of Stretched Systems:* every system is continuously stretched to operate at its capacity. People will exploit 'improvements,' for example, in the form of new technology, to better achieve goals by pushing the system out to operate near the edge of its new capacity boundaries. The process of adapting to exploit the improvement results in a new intensity, complexity, and tempo of activity.

The following empirical summary captures this dynamic, adaptive process and represents the findings from several researchers (Carroll et al., 1991; Winograd and Flores, 1986).

> Much of the equipment deployed…was designed to ease the burden on the operator, reduce fatigue, and simplify the tasks involved in operations. Instead, these advances were used to demand more from the operator. Almost without exception, technology did not meet the goal of unencumbering the personnel operating the equipment … Systems often required exceptional human expertise, commitment, and endurance …There is a natural synergy between tactics, technology, and human factors … Effective leaders will exploit every new advance to the limit. As a result, virtually every advance in ergonomics was exploited to ask personnel to do more, do it faster and do it in more complex ways…One very real lesson is that new tactics and technology simply result in altering the pattern of human stress to achieve a new intensity and tempo of operations. (Cordesman and Wagner, 1996, p. 25) [Edited to rephrase domain referents generically].

In adaptive cycles, designs act as stimulants in two major ways (Woods and Hollnagel, 2006). First, designs can trigger expansive adaptations by users and stakeholders that exploit capabilities as they seek to achieve their ends. When these expansive adaptations occur, we discover that people have exploited designs in ways typically unforeseen by the designers (Woods and Dekker, 2000). But, second, design change also can introduce impediments that create complexities to be adapted around and overcome – the workarounds often captured in compilations of designs with poor usability (Norman, 1988; Koopman and Hoffman, 2003). Though specific designs often create a mix of both affordances to be exploited and complexities to be worked around, and this mix can vary greatly for different people in different roles across an organization.

The epigraph to this section captures the basic concept: fielded designs have real effects on people in various roles, squeezing or enhancing their ability to express expertise. Designs can be examined in terms of how they release or undermine the cognitive skills of people as they carry out roles, handle changing situations, coordinate with other's activities, and adapt to meet goals. Good designs then release these skills and poor designs hinder or undermine people's ability to acquire or demonstrate cognitive skills (Norman, 1993; Bruner, 2003).

As Christopher Alexander (1977) noted, design has the special responsibility to connect technological capability to the adaptive power of people as goal-directed agents. Design should understand how skills, expertise, and adaptive capacity develop, how the work of designing can release these basic human processes, and how designs inadvertently can thwart these processes leaving people to act as though they were cognitively impaired (Woods et al., 1994, chapter 5). This chapter provides an introduction to some of the basic concepts about design and cognition. Mastery of these concepts will help design processes to enable or release human expertise, or, as Don Norman (1993) put it, how to innovate ' things that make us smart.'

A note about terminology – artifacts – People who write about cognition and design often use a neutral word for a designed interface, visualization, product, or object. They refer to these as artifacts since the object is just that, an object, until put in use by some person in some role. In use the physical thing or artifact is adapted to provide support. Through use the artifact becomes a cognitive tool in that it supports or enables people to exhibit skilled and coordinated activity. But many artifacts introduce complexities which add burdens to the people trying to carry out some activity in the world.

2. DESIGN AND COGNITION AT WORK: IMPAIRED OR UNIMPAIRED MICRO-COGNITION

To understand how properties of artifacts shape or influence cognition and activity, one has to appreciate some basics about cognition at work.

One dominant perspective about cognition focuses on mental processes, skills, and reasoning strategies as things that happen only 'in the head'. This is a micro-cognitive perspective (Klein et al., 2003). Micro-cognition refers to basic mental processes such as working memory that are believed to act as building blocks for more complex information processing. When cognition occurs only in someone's head, the processes are invisible. As a result, research methods focus on overcoming this difficulty using various techniques to make internal mental processes explicit and observable to outsiders.

For design, micro-cognition is concerned with the impact of a proposed or new artifact on the mental costs of carrying out the details of specific tasks and sub-tasks for their role. For example, designs can act as an external memory aids helping people call to mind relevant knowledge or designs can act as memory barriers forcing people to remember various codes and abbreviations in order to carry out their basic activities through that device. A quite common and relatively simple case occurs with alarm codes: Consider this example from NASA's mission control dialog over voice loops as the lunar lander descended to the moon during Apollo 11 (Murray and Cox, 1989).

> '1202.' Astronaut announcing that an alarm buzzer and light had gone off and the code 1202 was indicated on the computer display.
> 'What's a 1202?'
> '1202, what's that?'
> '12…1202 alarm.'

The alarms did not direct attention to the trouble or jump start diagnosis of the source of the anomaly or direct mission control's response to the anomaly. Instead, the alarm codes resulted in a memory bottleneck. People, without help from the external displays or representations, had to remember what each code stood for (Woods and Hollnagel, 2006).

This case is not just about alarms (or other examples of specific inscrutable codings), nor is it just a historical curiosity describing past designs. Many books continue to collect examples where the design of a device, interaction, or display turned out to increase memory demands on those using the artifact to accomplish something (e.g. Cooper, 1999). The impact of a design is summarized as a specific version of a very general story line – how a new artifact inadvertently created a bottleneck in micro-cognition. Often the demonstration of new memory bottlenecks produced by a design includes pictures of paper notes that users added to electronic systems as memory workarounds (e.g. users adding interpretive keys to overcome a bottleneck introduced by poor design).

From a micro-cognitive perspective, poor designs create or exacerbate bottlenecks in elemental cognitive processes. Inadvertently increasing memory demands is just one class of negative consequences of poor design on micro-cognition. Potential bottlenecks in micro-cognition include:

- Knowledge bottlenecks, i.e. the design makes it harder for people to call to mind knowledge relevant to the task at hand (Feltovich et al., 1997).
- Memory bottlenecks (Byrne and Bovair, 1997).
- Attention bottlenecks, i.e. the design makes it harder for people to switch attention between different threads of activity or lines of reasoning such as interruptions (Czerwinski et al., 1991).
- Workload bottlenecks, i.e. the design makes it harder for people to shift or prioritize workload to avoid risk of failure at workload peaks.
- Oversimplified mental models, i.e. the design makes it harder for people to develop appropriate and accurate models of how a device or process works (Kieras and Bovair, 1984; Cook et al., 1991).
- Intent bottlenecks, i.e. the design makes it harder for people to form coherent intentions to act given uncertainty and multiple goals which can conflict (see Kieras et al., 2001 on the modeling the translation of intention into action and see Cook, 2006, or Woods et al., 1994, chapter 4 for illustrative cases of managing goal conflicts in health care).

A good example is the bottlenecks that arise when poor design of transitions from one display to another as people perform interrelated tasks through a computer interface creates the keyhole effect (Woods and Watts, 1997). The keyhole effect occurs when people can only see a small portion of the relevant information space at one time. The keyhole effect creates a lack of peripheral awareness that can leave people lost in the display set and not know where to look next to find relevant information (an attentional bottleneck). The navigation workload goes up dramatically when there is a keyhole effect which leads to memory and knowledge bottlenecks as they must call to mind more information and remember more about where important data might be found among the many displays hidden behind the keyhole of the computer screen Watts-Perotti and Woods, 1999; Doherty and Upton, 2005). Another example is how the principles for designing direct manipulation interfaces have been validated by studies that show such designs eliminate micro-cognitive bottlenecks for memory and workload by connecting intentions to actions when people perform tasks via classic computer interfaces (Kieras et al., 2001).

Thinking about the relationship between cognition and design in terms of micro-cognition helps, but only within some very definite limits. Assessing the micro-cognitive consequences of designs is good for certain aspects of usability evaluation. If one has access to a prototyped or designed device that includes a partial specification of the tasks and sequences, of the procedures in different cases, and of the associated interactions and screen layouts, then one can use models of micro-cognition to detect memory and other bottlenecks. For example, micro-cognitive models have been used to predict long learning times and some types of basic task sequencing errors (Byrne and Bovair, 1997; Gray, 2007). In these cases, the specification of tasks is translated into a computerized cognitive model of micro-cognition (e.g. how working memory load varies as tasks are performed and how chunking occurs as a mechanism of learning from consistent experience over repeated tasks). When the computer simulation is able to carry out the task, one can use parameters of the underlying cognitive model to detect bottlenecks on working memory or long learning times (Bovair et al., 1990 provides one illustration of these tests).

But note there are several 'catches' in the relationship of micro-cognition to design. First, for design to use information about how an artifact impacts micro-cognition requires one first has a design! (or at least a partial design) since the tests require specification of the details of interaction. In other words, micro-cognition can be used to evaluate or test the impact of designs but cannot play a direct role in the processes of innovation necessary to generate useful or promising possibilities (Woods, 1998; Lee et al., 2006).

Second, micro-cognitive tests have difficulty detecting cumulative complexity that builds up as more and more features are added to a product over time in a competitive business environment (Lee et al., 2006). Each feature, looked at alone, appears to pass usability tests and to provide something for a use case or to compete with another product. Inadvertently, however, there is a cumulative complexity effect that comes to dominate any benefits added by each individual feature or option. Pragmatically, businesses have begun to notice the costs of cumulative complexity and the resulting risk of poor product performance in the competitive business landscape (Rust et al., 2006). Several companies and commentators have begun to call for reductions in the number of features on products in a search for a kind of simplicity (Pogue, 2005; Phillips Co., 2005; Wallace, 2006).

Third, by using micro-cognitive tests one can discover how a design hobbles cognition and retards learning, but one cannot discover new affordances that may lead to useful adaptations by practitioners that expand their ability to reach goals. These tests can identify how a design creates bottlenecks by forcing cognition to the micro-level so that the specific features that create complexity can be modified or repaired. But the tests do not contribute to the innovation processes that would lead to new concepts for products.

When users face complexities such as bottlenecks in micro-cognition, they work around them (e.g. Woods et al., 1994; Cook and Woods, 1996; Cook et al., 2000). It is interesting to note that this is one of the ways that the complexities are noted, not by measuring memory or workload bottlenecks directly, but by observing the workarounds people devise to avoid being hobbled too much by these sorts of complexity. The ways that users tailor their strategies, and the ways that they re-shape artifacts to workaround complexities and fill gaps act as pointers to other adaptive processes.

Designs can help foster expansive adaptations. But to do so, we need to look beyond bottlenecks in micro-cognition, and examine the functions of macro-cognition that link what people do, as responsible agents carrying out roles, to larger processes of coordinated activity and to larger functions such as anomaly recognition, sense making and replanning.

3. DESIGN AND COGNITION AT WORK: EXPANDING THE IMPACT OF MACRO-COGNITION

A broader perspective on cognition looks at how mental processes support coordinated activities in the world. Most vividly, it has been described as *cognition in the wild* (Hutchins, 1995) or cognition in *natural* settings (Klein, 1998) though other labels are joint cognitive systems (Hollnagel and Woods, 2005; situated cognition Suchman, 1987) or distributed cognition (Hutchins, 1995). This approach considers how macro-cognitive functions such as joint attention, anomaly recognition, replanning, sense making and others are situated in the context of human goals, desires, activity, and work (Klein et al., 2003; Klein et al., 2006a,b).

Macro-cognition moves away from an 'in the head' view of the internal processing of an individual because such a perspective loses sight of the active role of people in constructing meaning and exploring their environment. Micro-cognitive approaches to interaction design tend to get lost in a single person in front of a computer screen, missing how people engage in broader activities for larger purposes that move well beyond what appears on computer screens. Putting cognition in the world, or in the situation, emphasizes how people actively explore and find meaning in the world (Gibson, 1979).

> The ability to look, listen, smell, taste, or feel requires an animal capable of orienting its body so that its eyes, ears, nose, mouth, or hands can be directed toward objects and relevant stimulation from objects. Lack of orientation to the ground or to the medium surrounding one, or to the earth below and the sky above, means inability to direct perceptual exploration in an adequate way. (Reed, 1988, p. 227 on Gibson and perceptual exploration, in Gibson, 1966)

People as agents exist in an environment that is more than what can be seen directly. The actor's environment includes social structures, shared concepts, conventions, and human-fashioned artifacts. The active exploration process operates just as strongly when the people's experiences, observations, and actions are mediated by properties of digital media.

Heuristically, macro-cognitive functions can be grouped into a few categories of anomaly recognition, sense making, joint activity, and replanning.

Anomaly recognition – Noticing when events do not fit (or are beginning to deviate from) the current assessment or expectations (Woods and Hollnagel, 2006, Chapter 8). An anomaly is an event that produces a 'break' or interruption in the smooth flow of activity (Winorgrad and Flores, 1986). Attention, information search, explanation building (sense making), and problem solving then follow as one tries to understand the anomaly, what it means, and how to modify future actions. A simple example is software problems that occur when one is preparing material to meet a critical deadline – the break in flow occurs when the word processing software freezes. The crash produces a break in the activities enabled or empowered by the software; people's attention and resources have to flow to the software as an object in itself and away from the activity and its purpose.

Macro-cognitive studies examine what constitutes an anomaly, how people may overlook or discount anomalous indications or be very sensitive to early signs of trouble (Klein et al., 2005), and how recognizing an anomaly influences information search, explanation building and explanation revision (Woods, 1995a).

Sense making – How people find meaning in the data they see around them (Weick, 1995; Pirolli, 2007). People are explanation machines looking for meaning in what they experience (Bruner, 1990). Klein et al. (2006a,b) have proposed that sense making is built on how people frame and re-frame the events around them, where 'frame' refers to the perspective or context used to interpret the data or event in itself. The framing effect in psychology is the much replicated finding that changing the context can change how people see and interpret the very same data or event. In Klein's model, sense making refers to how people generate and modify the frame or context given the flow of experience (as opposed to the usual study that examines how the interpretation of the flow of experience changes if the larger frame called to mind changes.

For Klein et al. (2006b) sense making consists of how people *elaborate* a starting frame as new information comes in or new events occur, how they begin to *question* the current frame, and, eventually, how they look for a new frame to understand the events in question – *reframing*.

Sense making then is concerned with how people maintain a 'big picture' and avoid getting lost in the details surrounding a situation (or to use an aviation analogy, how to stay 'heads up' when there are many individual sub-tasks to be carried out which tend to take you 'heads down' in each), how people can demonstrate what Clausewitz in 1832 on the art of war called *coup d'oeil*, that is, how people can see at a glance the essential characteristic or leverage point in a complex situation (insight), how people are able to move from mere information gathering to develop syntheses and alternative explanations, how people are able to revise assessments and avoid being stuck in a one view, how people are able to develop broadening checks to help avoid premature closure on a weak assessment or explanation.

Interestingly, many of the aspects of sense making work best when they do not rely just on an expert individual but when they are part of collaborative interactions with others. For example, it can be very difficult for a single person to revise an assessment even as new evidence begins to accumulate that the assessment is incorrect (Feltovich et al., 2004). It is surprisingly easy to discount or rationalize away the new evidence and remain stuck in a previous assessment. Revision generally occurs when a fresh point of view enters the situation (Woods and Hollnagel, 2006). Errors in plans are best detected when cross-checks are built into a system by providing review over multiple and diverse perspectives (Patterson et al., 2004).

Joint activity – How to coordinate and synchronize activities that are distributed over multiple parties and artifacts (Hutchins, 1995; Sebanz et al., 2006). Moments of micro-cognition are part of and contribute to larger flows of interaction and coordination. For example, one often thinks of attention as a characteristic of an individual at some point in time – focused on one out of many activities, cues, or lines of thought. However, people demonstrate the ability to assess where another person's attention is focused and to follow another's focus, even at very young ages (Moore and Dunham, 1995). In addition, people signal to others where their attention is focused in order to influence where the other's attention will focus. This ability for *joint attention* illustrates how interpersonal cognitive capabilities play critical roles in processes of interaction and coordination across people. Joint attention turns out to be critical when different agents need to modify what they are doing when new events occur (Woods and Hollnagel, 2006).

Another part of joint attention is *judging the interruptibility of others*. Without this capability, miscoordination occurs where interruptions have high costs (Czerwinski et al., 1991; Ho et al., 2004). How technology is used influences joint attention as one kind of macro-cognitive function, for example the ability to listen in on other conversations by being part of a voice loop has been shown to be a critical contributor to very high levels of coordination in space shuttle mission control, even though from a micro-cognitive perspective the voice loop seems very noisy, confusing, and distracting (Patterson et al., 1999). Klein et al. (2005) describe various other functions that are necessary for joint action over multiple parties and roles. For example, maintaining and repairing common ground – a shared frame of reference about the activities and intentions going on – is a critical aspect of joint activity (Clark and Brennan, 1991; Monk, 2003).

Replanning – How to modify a plan in progress when disruptions occur or opportunities arise (Shattuck and Woods, 2000). Plans are always in motion at some time scale and there are degrees of commitment to planned actions ahead of a continuous rolling horizon. To modify plans in progress, participants need to be able to recognize unexpected events that disrupt the unfolding plans or unexpected events that provide new opportunities to achieve goals behind the plan.

It can be quite difficult to recognize when new events affect a plan in progress or to see all of the implications of a new event for the plan in progress. Replanning is an adaptive exercise adjusting or re-formulating a plan when new events introduce impasses or undermine the assumptions behind the plan. It may be even more difficult to recognize when new events provide new opportunities to achieve the goals behind the plan.

In replanning situations, people can often under-adapt by trying to continue the plan despite the disruptions (Woods and Shattuck, 2000). Or they can over-adapt – that is, they recognize events challenge the literal plan sequence, but their actions fail to respect many important constraints that had been considered in developing the original plan. New actions are taken to get around the specific disrupting event work around the disruption but these actions often have undesirable side effects because they fail to conserve other important aspects of the situation, original plan, and goals. This failure mode is referred to as – missing the side effects of changes to planned activities following changes in the external situation.

Replanning becomes more difficult as the plan involves more groups or organizations over wider ranges of space and time (Smith et al., 2007). Changing one aspect of a plan in progress can produce a cascade of modifications or even disruptions for other activities in motion by other groups. Assessing the impact and coordinating the adjustments is increasingly difficult as the time and spatial scale of the planned activities increases. Effective replanning depends on being able to see and track the cascades, reverberations, and side effects of new events and possible plan modifications.

4. CONTRASTING MICRO- AND MACRO-COGNITIVE VIEWPOINTS

Note the contrast of the list of macro-cognitive functions and the list of micro-cognitive bottlenecks. The macro-cognitive list refers to difficult capabilities that can be enabled or expanded through design of interactions, displays, and devices. The micro-cognitive list refers to troubles that arise when design hobbles people.

One can see the contrast in how each view approaches basic topics in workload and attention. Micro-cognition focuses on the limits of an individual to carry out mental operations and keep track of multiple lines of reasoning. Studies examine how people can time share or divide attention over different kinds of processing that could be required to execute various tasks, for example, listening to one conversation while visually controlling a dynamic process (such as occurs in driving a car while talking on a cell phone). The studies can help identify bottlenecks in workload and attention which could lead to poor performance (the cell phone conversation takes mental resources away from driving related tasks leading to poor vehicle control and slow responses to changes in the driving situation).

On the other hand, macro-cognition is interested in how people adapt to manage their tasks over time to avoid bottlenecks or how they prepare coping strategies to use should they be forced into a bottleneck situation. The starting point is in the world of activity, and the macro-cognitive observer notes that activity ebbs and flows, with periods of lower activity and more self-paced tasks interspersed with busy, high-tempo, externally paced operations where the quality of task performance is more critical.

As people learn where and when bottlenecks that threaten performance may occur, they can invoke some basic adaptive strategies (Woods and Hollnagel, 2006). They can develop a strategic response by either shifting some of the activity to other times to lower workload or by recruiting more resources, for example by bringing other people into the situation (for example, critical care physicians carry out these kinds of responses to reduce the chances of being trapped in a workload bottleneck should a patient's status deteriorate surprisingly; e.g. Cook and Woods, 1996). These adaptive responses depend on the ability to *anticipate potential upcoming bottleneck points* and the changing pressures on task performance as situations ebb and flow or vary being more routine or more exceptional. With anticipation one can recruit more resources such as extra staff, special equipment, additional expertise, or additional time, but since this strategy consumes organizational resources there can easily be pressures from above that restrict this strategic response. A part of expertise then consists of being able to anticipate potential bottlenecks and high tempo periods and to invest in certain tasks, or conserve certain resources, which reduce the risk of being caught in a bottleneck (and the accompanying risk of prioritizing the wrong parts or doing the whole task poorly) or being unable to cope with an anticipated bottleneck when it does occur. This becomes an illustration of the sense making macro-cognitive function at work and the sub-function of problem detection (Klein et al., 2005, 2006b). People may not always be good at sense making in situations with the potential for significant workload bottlenecks, but we can investigate the strategies experts use and which strategies work well in some situations to envision new promising possibilities for design.

From this short exploration of a single issue we can see the general contrast between the two perspectives on cognition and design. The micro-cognitive perspective provides concepts and tools to detect when design limits performance and can provide an impetus or justification for (but not innovate in) new design work – it initiates repair. In the case of cell phone distractions, if others have developed new designs, micro-cognitive tests can be carried out to see if attentional bottlenecks are reduced.

The macro-cognitive perspective generates directions to explore in the conceptual and ideation phases of design – it participates in innovation. And importantly, macro-cognitive results provide criteria that can be used to see if early design work will prove to be a promising direction that merits further investment of energy, talent, time and other design resources (rather than waiting for a prototype to be well specified enough to begin testing). Finally, macro-cognition provides a guide to create concrete scenarios that instantiate challenges for anomaly recognition, sense making, joint activity, and replanning as relevant to the scope of the design project. These scenarios can be used in envisioning and participatory design techniques and as test cases for evaluation.

From a macro-cognitive viewpoint, cell phones are just one of many additional tasks that can take driver's attention away from vehicle control and anticipating upcoming events. It is one example of a general problem created by new technology in the car – how to maintain a 'heads-up' or big picture view of the driving situation, despite the need or desire to perform many other 'heads-down' or secondary tasks. Heads-up is a label that comes from aviation. It refers literally to looking out the window and figuratively to the sense making processes that allow one to maintain a big picture view of the priorities for the context. Heads-down literally refers to looking at one of the many interfaces or devices used for secondary tasks that require drivers or pilots to look down inside the cockpit or cab; the label has the connotation of getting lost in details. New tools are being devised especially for aviation that help pilots shift attention to the big picture by using tactile signals to indicate the need to shift out of secondary tasks and re-examine the strategic situation (achieving joint attention while judging interruptability; see Ho et al., 2004).

5. MACRO-COGNITION AND EXPANSIVE ADAPTATIONS

Often new technological developments are important because they have the potential to change how macro-cognitive functions are carried out. Effective leaders and innovators will discover ways to exploit the new technological power to better achieve goals which will either require or result in changes in macro-cognitive functions. One ongoing trend is new sensor, robotic, and networking technology that makes it possible for macro-cognitive functions to be extended over much larger fields of available information and over a larger set of relevant stakeholders. This power – broader connection across groups that are physically separated – is exploited to achieve more, more quickly (e.g. global product engineering networks that speed product development). This new organization enabled by the technology for connectivity at distance expands the scope of sense making and replanning activities over new groups and new relationships. But the tools that support sense making and replanning also change when the scope changes. How will engineers in Bangalore, Seattle, and Moscow collaborate to maintain seeing the big picture as the work encounters obstacles? How will the groups track the reverberations of design changes to avoid missing side effects of change decisions? How will one group realize the new opportunity represented by an advance developed by another group in another part of the world? The process of transformation triggered by new technology changes the demands placed on macro-cognition, changes the affordances for support of macro-cognition, and requires new innovative design efforts to build new support tools. For example, simply copying the devices and displays that support collocated teams and re-using them when teams are distributed has led to lower performance on macro-cognitive functions (Hinds and Kiesler, 2002).

Macro-cognitive functions are resources people use to cope with change as well. To the degree a team or organization is better able to do anomaly recognition, sense making, joint activity, and replanning, they will also be better able to adapt to change by avoiding unnecessary complexity. When people can perform macro-cognition effectively, they are better able to exploit change to achieve more while managing the side effects and tradeoffs produced by those changes.

When macro-cognitive functions are effective, what dimensions of adaptive capacity expand? The answer is three fold; macro-cognitive capability expands the following:

1. The ability to be *resilient* when situations challenge the boundary conditions of normal practices or when surprising situations occur; macro-cognitive functions support how systems can be resilient when surprises occur and to manage the unexpected (anomaly recognition, reframing).
2. The scope of potential control by better *coordinating* activity over multiple people and groups in different roles; macro-cognitive functions support coordinated and not fragmented activity as multiple parties become more closely tied together (joint activity, replanning).
3. The scope and distances over which people can search for or create *meaning* and then project their intent from a distance; macro-cognition supports how people can project themselves into and make sense of remote settings relative to different purposes (sense making and replanning).

Each of these three kinds of adaptive capability is the necessary complement to a vector of technology change. Inevitably, new technological powers are adapted to re-shape what we do, how we do it, and why we do it. Each form of technological power constitutes an *infrastructure* which demands a new *superstructure* (of resilience, coordination, and sense making, respectively) that works in parallel.

The first dimension of adaptation – resilience – is a critical complementary partner to technological developments that tightly couple together different parts of a larger process or system for hyper-efficiency. A variety of technological powers are tapped in order to squeeze systems of human activity to be more and more optimal. In parallel, these systems become more brittle and can fail dramatically when surprising situations arise – situations which challenge the boundary conditions of textbook operation (Hollnagel et al., 2006). As systems of activity become larger but more tightly coupled, surprising conditions arise in part because a single anomaly will cascade and spread through the system quickly (e.g. modern supply chains in business). Rather than be trapped in workload bottlenecks, experts add resilience to systems by anticipating to avoid workload bottlenecks or by anticipating and preparing coping strategies so that the appropriate priorities are maintained even if outside events should force workload bottlenecks onto the people responsible.

The second dimension of adaptation – coordination – is a critical complementary partner to the technological development of ubiquitous connectivity. The technology of connection by itself does not create coordination, rather it represents underlying powerful infrastructure that is adapted in ways that re-shape how and when we interact with others in what we seek to accomplish.

The infrastructure for connectivity, then, challenges our ability to design superstructures that coordinate non-co-located activities and asynchronous activities over greater ranges (Hinds and Kiesler, 2002). Good designs will trigger adaptations that support coordination; poor designs will lead to fragmentation and breakdowns at the boundaries of the different groups or roles (e.g. coordination surprises; Woods and Hollnagel, 2006).

The third dimension of adaptation – meaning finding – is a critical complementary partner to the technological developments that combine virtual worlds, new sensor technologies and the ability to shift virtual point of observation with new '3-D' technologies. These powers allow people to virtually stand in places that would be too difficult, expensive, dangerous or impossible to reach physically. How do we make sense of these remote situations? For example, the current video feeds from robots in search and rescue tasks undermine all of the perceptual skills of people naturally bring to bear when they are present in a scene (Murphy and Burke, 2005; Woods et al., 2004).

The infrastructure of mobile remote sensing (and how to combine these different types of data about the world) demands a new superstructure for sense making as people can 'forage' more widely for relevant data and project themselves into distant situations (Pirolli and Card, 1999; Woods et al., 2002).

Smith et al. (2007) provide a good example of the connections between infrastructure change and superstructure response that depends on designing affordances to support macro-cognitive functions. Under increasing economic pressure, air traffic control needed to change in order to provide greater flexibility in tailoring and modifying flight plans to match varying congestion points and the changing costs of routing aircraft to destinations. Technological changes made adopting new digital communication infrastructure readily obtainable, and this new capability appeared to allow for much greater flexibility in flight planning and replanning. However, the infrastructure change, while necessary, was insufficient alone without a parallel and complementary change in the superstructure for coordination across multiple groups, especially given changes in weather and failures that could reduce airport capacity. Changing the patterns of coordination over the multiple parts of the national air traffic system was needed so that the system could adapt gracefully and intelligently when disrupting events occurred. Designing the collaborative information and display systems that support distributed work across airline dispatch and strategic and regional air traffic control centers, as situations change, required new design to support macro-cognitive functions (Klein et al., 2005):

- Joint activity required tools for building common ground to help recognize anomalies.
- Replanning required synchronized joint activity to consider all of the ramifications of a disrupting event or plan modification.
- Shared sense making needed new forms of exchange of information and perspective to recognize when strategic adjustments were necessary.

6. INVENTING THE FUTURE OF COGNITION AT WORK

Design changes cognition. By introducing artifacts that mediate information pick up, interaction, and goal-directed action, design influences both micro- and macro-cognition. This is a fundamental finding in cognition – often called the representation effect (Norman, 1993; Zhang and Norman, 1994; Woods, 1995b).

Design can impair micro-cognition creating bottlenecks that make it easy to see people as highly limited processors. Adding complexities makes interaction clumsy, makes attention flow to the device itself, rather than the larger goal-directed activity. These impairments add significant costs that limit people and lead to workaround and gap-filling forms of adaptation. Finding bottlenecks and workarounds initiates repair of past design.

Alternatively, design produces affordances – support for the difficult macro-cognitive functions of anomaly recognition, sense making, joint activity, and replanning. These advances release the growth of expertise as people learn and share ways to manage the complexities and tradeoffs that challenge all aspects of human activity in our uncertain, changing worlds.

These twin effects of designs – clumsiness relative to micro-cognition and affordances relative to macro-cognition – will trigger people, acting in various roles to achieve multiple goals, to adapt. These adaptations may be workarounds to cope with complexities and bottlenecks – gap-filling adaptations. The adaptations may be transformations that exploit new capabilities and that result in new demands and pressures on systems and on human roles in those systems – expansive adaptations. Ironically, these latter act as transformative adaptations (Winograd and Flores, 1986; Woods and Dekker, 2000) which feed back on cognition to create new demands and constraints on carrying out macro-cognitive functions and new costs for micro-cognitive bottlenecks. As has been noted before, in adaptive cycles, today's design solutions will produce surprises that become tomorrow's design challenges.

REFERENCES

Alexander, C. (1977). *A pattern language: buildings, towns, and cities*. New York: Oxford University Press.

Bovair, S., Kieras, D. E. and Polson, P. G. (1990). The acquisition and performance of text-editing skill: a cognitive complexity analysis. *Human-Computer Interaction*, *5(1)*, 1–48.

Bruner, J. (1990). *Acts of meaning*. Cambridge, MA: Harvard University Press.

Bruner, J. (2003). The narrative construction of reality. In: M. Mateas and P. Sengers (Eds.) *Narrative intelligence*. Philadelphia, PA: J. Benjamins.

Byrne, M. D. and Bovair, S. (1997). A working memory model of a common procedural error. *Cognitive Science*, *21*, 31–61.

Carroll, J. M., Kellogg, W. A. and Rosson, M. B. (1991). The task-artifact cycle. In: J. M. Carroll (Ed.) *Designing interaction: Psychology at the human-computer interface*. Cambridge: Cambridge University Press.

Carroll, J. M. (Ed.) (2003). HCI models, theories, and frameworks: Toward a multidisciplinary science. Boston: Morgan Kaufmann.

Clark, H. and S. Brennan, S. (1991). Grounding in communication. In: L. Resnick, J. M. Levine and S. D. Teasley (Eds.) *Perspectives on socially shared cognition*, pp. 127–149.Washington, DC: American Psychological Association.

Clausewitz, C. (1968, original 1832). *On war*, p. 141. London: Penguin.

Cook, R. I., Potter, S., Woods, D. D. and McDonald, J. S. (1991). Evaluating the human engineering of microprocessor controlled operating room devices. *Journal of Clinical Monitoring*, *7*, 217–226.

Cook, R. I. and Woods, D. D. (1996). Adapting to new technology in the operating room. *Human Factors*, *38(4)*, 593–613.

Cook, R. I., Render M. L. and Woods, D. D. (2000). Gaps in the continuity of care and progress on patient safety. *British Medical Journal*, *320*, 791–794.

Cook, R. I. (2006). Being bumpable. In: D. D.Woods, and E. Hollnagel. *Joint cognitive systems: Patterns in cognitive systems engineering*. Boca Raton, FL: Taylor and Francis.

Cooper, A. (1999). *The inmates are running the asylum: Why high tech products drive us crazy and how to restore the sanity*. Indiana: Sams.

Cordesman, A. H. and Wagner, A. R. (1996). *The lessons of modern war*, *Vol. 4: The Gulf War*. Boulder, CO: Westview Press.

Czerwinski, M., Chrisman, S. and Schumacher, B. (1991). The effects of warnings and display similarities on interruptions in multitasking environments. *SIGCHI Bulletin*, *23(4)*, 38–39.

Doherty, G. and Upton, C. (2005). Designing displays for mobile decision support. L. MacKinnon, O. Bertelsen and N. Bryan-Kinns (Eds.) *Proceedings of 19th BCS Conference on Human Computer Interaction* (HCI 2005), Vol. 2, pp. 83–88.

Ericsson, K. A., Charness, N., Hoffman, R. R. and Feltovitch, P. J. (Eds.) (2006). *The Cambridge handbook on expertise and expert performance*. Cambridge: Cambridge University Press.

Feltovich, P. J., Ford, K. M. and Hoffmann, R. R. (Eds.) (1997). *Expertise in context: Human and machine*. Cambridge, MA: MIT Press.

Feltovich, P. J., Hoffman, R. R., Woods. D. D. and Roesler, A. (2004). Looking at cognitive engineers doing cognitive engineering: Implications of the reductive tendency for the design of complex sociotechnical systems. *IEEE Intelligent Systems*, May/June, 90–94.

Flach, J. and Hoffman, R. R. (2003). The limitations of limitations. *IEEE Intelligent Systems*,*18(1)*, 94–97.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Gilovich, T., Griffin, D. and Kahneman, D. (Eds.) (2002). *Heuristics and biases: The psychology of intuitive judgment*. New York: Cambridge University Press.

Gigerenzer, G. (2000). *Adaptive thinking*. New York: Oxford University Press.
Gray, W. D. (Ed.) (2007). *Integrated models of cognitive systems*. New York: Oxford University Press.
Hinds, P. and Kiesler, S. (Eds.) (2002). *Distributed work*. Cambridge, MA: MIT Press.
Ho, C.-Y., Nikolic. M., Waters, M. and Sarter, N. B. (2004). Not now: Supporting interruption management by indicating the modality and urgency of pending tasks. *Human Factors*, *46(3)*, 399–409.
Hoffman, R. R., Roesler, A. and Moon, B. M. (2004). What is design in the context of human-centered computing? *IEEE Intelligent Systems*, *19(4)*, 89–95.
Hollnagel, E. and Woods, D. D. (2005). *Joint cognitive systems: foundations of cognitive systems engineering*. Boca Raton, FL: Taylor and Francis.
Hollnagel, E., Woods, D. D. and Leveson, N. (Eds.) (2006). *Resilience engineering: Concepts and precepts*. Aldershot: Ashgate.
Hutchins, E. (1995). *Cognition in the wild*. Cambridge, MA: MIT Press.
Kahneman, D. and Tversky, A. (1996). On the reality of cognitive illusions: A reply to Gigerenzer's critique. *Psychological Review*, *103*, 582–591.
Kiesler, S. and Hinds, P. (Eds.) (2004). *Human-robot interaction: A special double issue of human–computer interaction*. Hillsdale, NJ: Lawrence Erlbaum.
Kieras, D. E. and Bovair, S. (1997). The role of a mental model in learning to operate a device. *Cognitive Science*, *8*, 255–273.
Kieras, D. E., Meyer, D. and Ballas, J. (2001). Towards demystification of direct manipulation: Cognitive modeling charts the gulf of execution. In: M. Beaudouin-Lafon, and R. J. K. Jacob (Eds.) *Proceedings of the ACM CHI 2001 Human Factors in Computing Systems Conference*, pp. 128–135. Seattle, Washington, USA.
Klein, G. A. (1998). *Sources of power: How people make decisions*. Cambridge, MA: MIT Press.
Klein, G. A., Ross, K. G., Moon, B. M., et al. (2003). Macrocognition. *IEEE Intelligent Systems*, *18(3)*, 81–85.
Klein, G., Feltovich, P., Bradshaw, J. M. and Woods, D. D. (2005). Common Ground and Coordination in Joint Activity. In W. Rouse and K. Boff (Ed.) *Organizational simulation*, pp. 139–178. NY: Wiley.
Klein, G., Pliske, R., Crandall, B. and Woods, D. (2005). Problem detection. *Cognition*, *Technology*, *and Work*, *7(1)*, 14–28.
Klein, G. A., Moon, B. and Hoffman, R. R. (2006a). Making sense of sensemaking 1: Alternative perspectives. *IEEE Intelligent Systems*, *21(4)*, 22–25.
Klein, G. A., Moon, B. and Hoffman, R. R. (2006b). Making sense of sensemaking 2: A macrocognitive model. *IEEE Intelligent Systems*, *21(6)*, 22–26.
Koopman, P. and Hoffman, R. R. (2003). Work-arounds, make-work, and Kludges. *IEEE Intelligent Systems*, *18(6)*, 70–75.
Lee, D.-S., Woods, D. D. and Kidwell, D. (2006). Escaping the design traps of creeping featurism: Introducing a fitness management strategy. *Usability Professionals' Association Annual Conference*, Broomfield, Colorado, June 12–16, 2006.
Moore, C. and Dunham, P. (Eds.) (1995). *Joint attention: Its origins and role in development*. Hillsdale, NJ: Lawrence Erlbaum Associates.
Monk, A. (2003). Common ground in electronically mediated communication. In: J. M. Carroll (Ed.) *HCI models*, *theories*, *and frameworks: Toward a multidisciplinary science*, pp. 265–290. Boston: Morgan Kaufmann.
Murphy, R. R. and Burke, J. L. (2005). Up from the rubble: Lessons learned about HRI from search and rescue. In: *Proceedings of the 49th Annual Meeting of the Human Factors and Ergonomics Society*, Orlando, FL, Sep. 26–30, 2005. Human Factors and Ergonomics Society.
Murray, C. and Cox, C. B. (1989). *Apollo*, *The race to the moon*. New York: Simon and Schuster.
Neisser, U. (1976). *Cognition and reality*. San Francisco: W. H. Freeman.
Norman, D. (1988). *The psychology of everyday things*. New York: Doubleday.
Norman, D. A. (1993). *Things that make us smart*. Boston: Addison-Wesley.
Patterson, E. S., Watts-Perotti, J. and Woods, D. D. (1999). Voice loops as coordination aids in space shuttle mission control. *Computer Supported Cooperative Work*, *8(4)*, 353–371.
Patterson, E. S., Cook, R. I., Woods, D. D. and Render, M. L. (2004). Examining the complexity behind a medication error: Generic patterns in communication. *IEEE SMC Part A*,*34(6)*, 749–756.
Philips. (2005). *Why simplicity?* Available from: http://www.philips.com/about/brand/whysimplicity/
Pirolli, P. and Card, S. K. (1999). Information Foraging. *Psychological Review 106(4)*, 643–675.
Pirolli, P. (2007). *Information foraging: Adaptive interaction with information*. New York: Oxford University Press.
Pogue, D. (2005). The cellphone that does everything imaginable, at least sort of. *NY Times*, May 12, 2005.
Reed, E. S. (1988). *James J. Gibson and the psychology of perception*. New Haven, CT: Yale University Press.

Rust, R. T., Thompson, D. V. and Hamilton, R. W. (2006). Defeating feature fatigue. *Harvard Business Review*, February 2006.
Schmorrow, D. D. (Ed.) (2005). *Foundations of augmented cognition*. Hillsdale, NJ: Lawrence Erlbaum.
Sebanz, N., Bekkering, H. and Knoblich, G. (2006). Joint action: Bodies and minds moving together. *Trends in Cognitive Sciences*, *10*, 70–76.
Shattuck, L. G. and Woods, D. D. (2000). Communication of intent in military command and control systems. In: C. McCann and R. Pigeau (Eds.) *The human in command: exploring the modern military experience*, pp. 279–292. New York: Kluwer Academic/Plenum Publishers,
Smith, P. J., Spencer, A. L. and Billings, C. E. (2007). Strategies for designing distributed systems: Case studies in the design of an air traffic management system. *Cognition*, *Technology and Work*, *9* (in press). [AU2]
Suchman, L. (1987). *Plans and situated action.* NY: Cambridge University Press.
Thomas, J. J. and Cook, K. A. (2005). *Illuminating the path: The research and development agenda for visual analytics*. NY: IEEE Computer Society.
Wallace, R. (2006). Be smart, be simple. *DMI Review Article*, *17(2)*, Spring 2006.
Watts-Perotti, J. and Woods, D. D. (1999). How experienced users avoid getting lost in large display networks. *International Journal of Human-Computer Interaction*, *11(4)*, 269–299.
Weick, K. E. (1995). *Sensemaking in organizations*. Thousand Oaks, CA: Sage Publications.
Winograd, T. and Flores, F. (1986). *Understanding computers and cognition.* Norwood, NJ: Ablex.
Woods, D. D., Johannesen, L., Cook, R. I. and Sarter, N. (1994). *Behind human error: Cognitive systems*, *computers and hindsight.* Human Systems Integration Information and Analysis Center, WPAFB, Dayton OH. (available at http://www.hsiiac.org/hsi/products.do?action=detailandcode=HS-1994-2).
Woods, D. D. (1995a). The alarm problem and directed attention in dynamic fault management. Ergonomics, 38(11), 2371–2393.
Woods, D. D. (1995b). Towards a theoretical base for representation design in the computer medium: Ecological perception and aiding human cognition. In: J. Flach, P. Hancock, J. Caird, and K. Vicente (Eds.) *An ecological approach to human machine systems: A global perspective*. Mahwah, NJ: Lawrence Erlbaum.
Woods, D. D. and Watts, J. C. (1997). How not to have to navigate through too many displays. In: M. G. Helander, T. K. Landauer and P. Prabhu (Eds.) *Handbook of human-computer interaction* (2nd Ed.) Amsterdam, The Netherlands: Elsevier Science.
Woods, D. D. (1998). Designs are hypotheses about how artifacts shape cognition and collaboration. *Ergonomics*, *41*, 168–173.
Woods, D. D. and Shattuck, L. G. (2000). Distant supervision – local action given the potential for surprise. *Cognition*, *Technology and Work*, *2*, 242–245.
Woods, D. D. (2002). Steering the reverberations of technology change on fields of practice: Laws that govern cognitive work. *Proceedings of the 24th Annual Meeting of the Cognitive Science Society*. [Plenary Address] [AU3]
Woods, D. D., Patterson, E. S. and Roth, E. M. (2002). Can we ever escape from data overload? A cognitive systems diagnosis. *Cognition*, *Technology*, *and Work*, *4(1)*, 22–36.
Woods, D. D. and Hollnagel, E. (2006). *Joint cognitive systems: Patterns in cognitive systems engineering*. Boca Raton, FL: Taylor and Francis.
Zhang, J. and Norman, D. A. (1994). Representations in distributed cognitive tasks. *Cognitive Science*, *18*, 87–122.

AUTHOR QUERIES

[AU1] AU: please check that this Xref is correct
[AU2] AU: Published yet? Please give pages.
[AU3] AU: Please give location.