Directive Displays: Supporting Human-machine Coordination by Dynamically Varying Representation, Information, and Interjection Strength

A Dissertation

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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2013

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Abstract

The ability of decision-support technology to function as a "team player" in directing attention and conveying relevant information is a critical component of system coordination. Good coordination, although effortful, increases overall system resilience as differences in knowledge and expertise of the technology and human agents can complement each other. In addition, a shared common ground among agents facilitates consistent priorities across the system, helping all agents to know when and how to interject as new events arise. Based on complementary theoretical frameworks for directing attention and human-machine coordination, a new class of decision-support was created, a directive display. Directive displays provide alternatives to text-based alerts by reconceptualizing the decision support design architecture into four distinct evidence-based design dimensions: representation type, information type, information delivery, and interjection strength. By explicitly selecting options from each dimension, directive displays dynamically change their design based on situational factors.

Three studies were conducted to determine the relative effectiveness of directive displays in reducing inappropriate diagnostic imaging, a timely issue due to the recent increased awareness of its associated patient risk and cost. The first study used data collected from an academic medical center's information warehouse to determine the impact of changes in computed tomography (CT) volume and dose reduction strategies

on patient exposure to ionizing radiation. It was hypothesized that the combined reductions of imaging volume and radiation dose per image would reduce patient exposure. This hypothesis was confirmed by the findings, with the combination of decreased CT volume and decreased dose per image reducing patient exposure by 63%. The second study was a between-subject study in a simulated setting that determined the comparative effectiveness of directive displays relative to baseline clinical alerts in reducing inappropriate imaging. It was hypothesized that physicians using directive displays would reduce inappropriate imaging orders. Findings from this study confirmed that directive displays were more effective at reducing inappropriate imaging for both routine and novel patients, including those for which the technology had incomplete or incorrect information. The third was a descriptive study using participatory design methods to better understand the framework of decision factors physicians use to determine whether or not to ordering diagnostic imaging. It was found that the ability for a test to provide actionable information for patient diagnosis was consistently prioritized over considerations of patient safety, blunt end constraints, or patient comfort.

These findings indicate that a non-interrupting directive display that is always visible is a viable and superior alternative to interrupting textual alerts that are commonly found in clinical decision support. It is anticipated that directive displays may be able to overcome common decision support vulnerabilities for other applications, especially in settings with high variability in uncertainty and consequences, because of their ability to dynamically select contextually appropriate design options within the four design dimensions. As this high variability is common for many complex sociotechnical systems, there are many potential future applications for directive displays. Future research directions are discussed, including new settings that may be well suited to directive displays and exploration into multimodal directive displays.

Dedication

To Sarah for keeping a mirror in front of my face, and to Henry and Emerson for timely hugs that ensure that I keep everything in perspective.

Acknowledgements

I thank Dr. Emily Patterson for making this PhD journey possible. Her guidance and patience through my progression has been invaluable and appreciated. I thank Dr. Elizabeth Sanders for her continued support and insights as I try to integrate design thinking and a scientific approach to seek understanding and create solutions. I thank Dr. Nina Kowalczyk for providing a fresh perspective and bolstering my understanding of advanced diagnostic imaging. I thank Dr. Beth Liston for sharing her clinical perspective to ensure authenticity in our research and for being its clinical champion.

I thank Dr. David Woods and Dr. Phil Smith, who have continued mentoring me, enhancing my understanding of cognitive systems engineering and providing valuable insights to ensure that I do not stray too far from what they initially taught me. Their decade of support is very appreciated.

I thank the numerous clinicians at The Ohio State University Wexner Medical Center who have agreed to participate and have assisted in recruiting in these studies.

I would like to thank my family, who endured every trial and tribulation with me, offering me support and encouraging me. I would also like to thank the HRS cohort who adopted me, and Nora Fritz whose progress allowed me to see what each next step would entail.

Funding for this research was provided by the Office of Naval Research's (ONR's) Command Decision Making program (N00014-11-1-0222). The views are those of the author and not necessarily the Navy.

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Fields of Study

Major Field: Health and Rehabilitation Sciences

Minor Field: Cognitive Systems Engineering

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Chapter 1: Introduction

The purpose of this Dissertation is to (1) provide a cognitive systems framing for the issues involved in designing technology meant to support decision-making under uncertainty and directing attention in complex sociotechnical systems, (2) show how a new type of decision support, a directive display, is superior to a traditional alerting system in improving system performance when data available to it is incomplete or incorrect, and (3) introduce a novel framing of decision aids that led to directive displays and describe how their dynamic, context-sensitive use of aspects of other classic design composites excel where uncertainty, surprise, and consequences are highly variable and interruptions are undesirable.

A Cognitive Systems Approach

Directive displays are primarily meant to support joint decision making in complex sociotechnical systems, although they may be useful in other settings as well. These systems have high consequences for failure and are semantically complex and time pressured (Cook & Woods, 2010) . To understand and improve the performance of these systems, a cognitive systems approach mitigates the risk of arriving at oversimplified conclusions that obscure or altogether miss the true system dynamics at work, thereby inadvertently adding additional burdens to the system (Woods & Roth, 1998).

In studying complex worlds from this perspective, the foundational principal is that practitioners' observable behaviors are the result of coping with the demands and constraints, both seen and unseen, imposed on them by their surroundings (Woods, 1988). It requires that the smallest unit of analysis be a complex conglomerate of people (agents), tools (artifacts) and their setting (world). This "cognitive triad" (Woods, 1988; Woods & Roth, 1998), seen in Figure 1.1, cannot be fully decomposed into its component parts. This perspective has its roots in earlier ecological work focused on agent-environment mutuality, which states that a person's behavior cannot be understood without understanding the environment in which it is observed (Gibson, 1979).

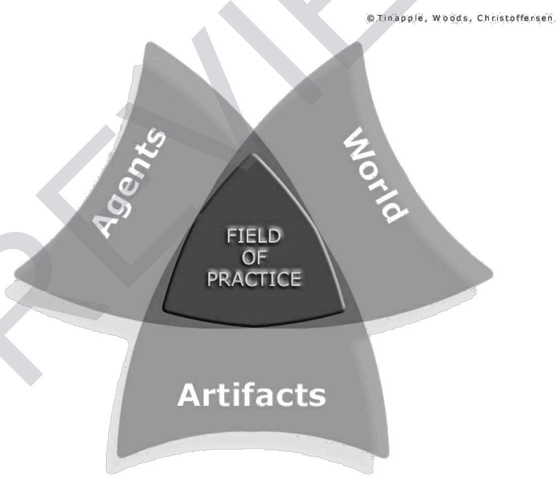

Figure 1.1: Cognitive triad (Tinapple, Woods, Christoffersen, 1988)

Directing Attention

Using this perspective as a guide, a critical component in decision support design is being able to understand how the new technology (artifact) will compete for the attention of operators (agents) in a specific setting (world) of interest. An enduring model of attention as a cycle of perception and action was first proposed by Neisser (1976), which is shown in Figure 1.2. It shows that (1) agents use their mental schema, directing exploration in the environment to (2) sample the environment (or an object in the environment) which then (3) generates stimuli which modifies the mental schema of the agent, which is again used to select and implement an action to direct subsequent exploration.

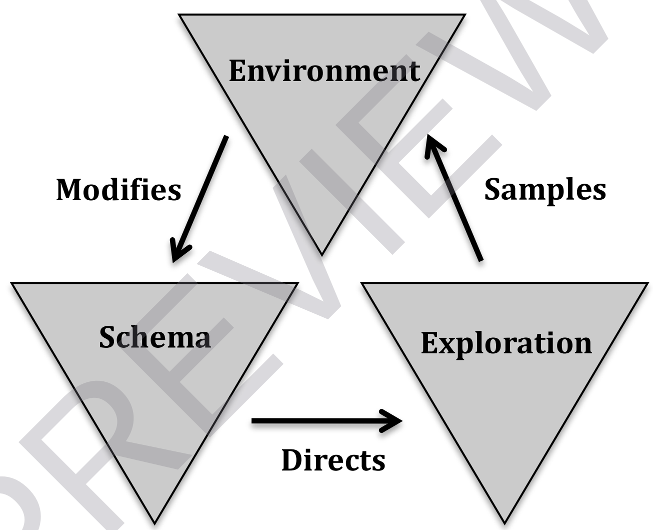

Figure 1.2: Neisser perception-action cycle (1976)

This cycle was adapted by Rayo et al. (2012) to describe and predict human operators' initial responses to a given technology's signal to direct attention, which is shown in Figure 1.3. In it, changes in the environment (i.e., an event) produce signals from the technology which are then detected by the operator. If the event is detected, preattentive processes (Broadbent, 1977) must discern if the emergent event is of sufficient priority to redirect attention from what is currently being attended to. Depending on that reprioritization, foveal attention will either stay on the current task or tasks, be fully redirected to the new event, or will be divided between them (Gopher, 1993; Pashler, Johnston, & Ruthruff, 2001). This action will ostensibly lead to receiving additional feedback, restarting the cycle. The first two processes, detection and reprioritization of attention, can be thought of as sequential gates that preclude any action selection or implementation based on the new stimuli.

Potential obstacles to the detection of new events include insufficient salience, one signal masking another, saturation of one or more sensory modalities, inability to recall the meaning of a given signal, and presenting a signal outside of a given sensory modality's range (Nikolic, Orr, & Sarter, 2004; R. Patterson, 1989; Rayo et al., 2012).

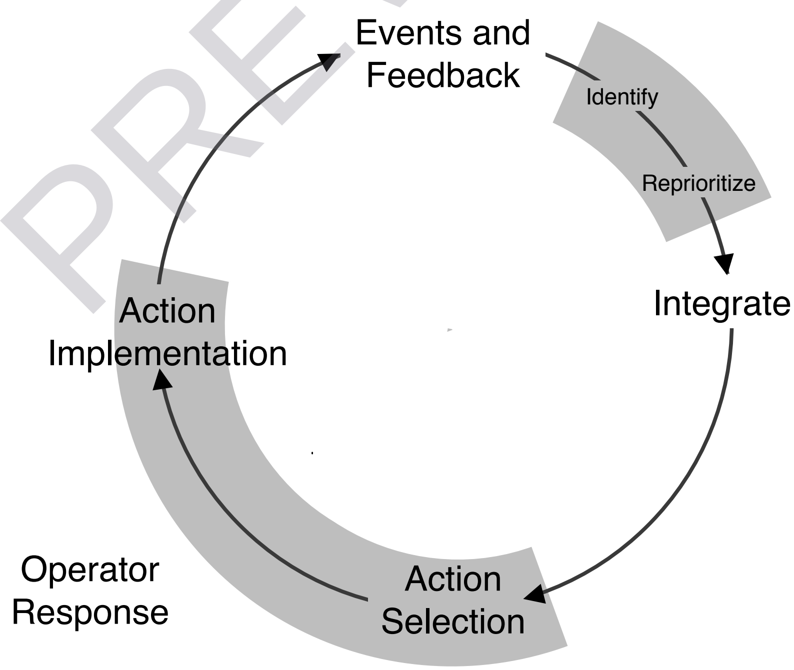

Figure 1.3: Adapted perception-action cycle by Rayo et al. (2012)

The most common obstacle to any detected signal's ability to reprioritize foveal attention is its lack of information content (Woods, 1995). This is usually due to the signal having low positive predictive value (PPV), which is the proportion of times where the signal's warning corresponds to the occurrence of the event of interest is actually occurring (J. Meyer & Bitan, 2002). As false alarms increase, positive predictive value decreases. Low PPV has been shown to result in the increased likelihood of the receiving agent disregarding the signal (Bliss, Gilson, & Deaton, 1995; Sorkin & Woods, 1985; Woods, 1995). Low information content can also be a result of a single signal being used for multiple events or event urgencies, with similar results (Woods, 1995).

Coordination

More sophisticated coordination between humans and machines becomes necessary as technology is more involved in decision-making. This is in stark contrast to the common belief that increasing the autonomy of automation reduces the role of the human operator (Woods & Hollnagel, 2006). It has been found that that the inclusion of a decision-making agent can lead to many forms of automation bias (Parasuraman & Manzey, 2010), alarm overload (Woods, 1995) and ungraceful transitions of authority (Woods & Hollnagel, 2006). Overcompliance occurs when human operators overestimate the veracity of the automation's guidance, where guidance that was meant to designate the possibility of an event is interpreted as proof of that event occurring (J. Meyer, 2001). Whereas the consequences of overcompliance can be benign, they can be severe in novel situations where the automation is operating outside of the boundaries of its design, a common form of brittleness (Roth, Bennett, & Woods, 1987; Smith, McCoy, & Layton,