SYNTHETIC TASK ENVIRONMENTS AND THE THREE BODY PROBLEM

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The challenge for our panel was to address the opportunities and challenges of synthetic task environments for basic research on human performance in sociotechnical systems. In doing this, the classical three-body problem from physics is used as a metaphor to illustrate the contrast between dyadic and triadic semiotic models of cognitive systems. In the context of this metaphor, synthetic task environments offer a means to bring some of the additional complexities of triadic semiotic systems under experimental control where converging empirical methods can help to titrate through the additional complexity to distill basic theoretical insights that will potentially have practical value for training and interface design.

This paper will begin by examining two alternative perspectives on semiotic or cognitive systems – the dyadic and the triadic perspectives. The case will be made that the triadic perspective provides a more comprehensive framework for exploring cognition and the pragmatic implications for the design of sociotechnical systems (e.g., next generation air space control systems). However, the introduction of a 'third body' into the cognitive system raises important challenges for both science and application. The paper will consider the challenges of the triadic (three-body) system and will suggest how synthetic task environments can help researchers to address these challenges.

Semiotics

The theoretical context for cognitive science and for its application to the design of sociotechnical systems was strongly influenced by the field of semiotics. Semiotics is typical described as the science of signs, but it can also be described as the science of meaning making. That is, the focal question of semiotics is how meaning is attributed to signs or representations. Ferdinand Saussure and Charles Sanders Peirce are typically credited with independently founding the field of semiotics (Eco, 1979, Morris, 1971). However, they approached the problem from two distinct perspectives.

Sausure's Dyadic Semiotic System

Saussure, generally regarded as the father of linguistics, framed the semiotic system in terms of the dyadic relation between a sign/symbol and an agent/observer, as illustrated in Figure 1. Saussure's interest was particularly in the evolution of alphabets and languages. Thus, he viewed the semiotic problem from the perspective of assigning meaning to symbols (e.g., written or spoken language). This framework fit ideally with the computer metaphor of mind and it set the stage for the first wave of cognitive science and the information processing approach to cognition and design. In this context, the cognitive agent was considered to be a symbol processor and the focus of basic research was on exploring the internal information processing constraints (e.g., channel capacity and internal recoding). The focus for application of this approach involved characterizing the internal information constraints so that these constraints could be considered in designing cognitive work (e.g., don't overload the limited capacity working memory).

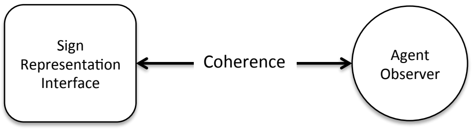

Figure 1. This diagram illustrates Saussure's dyadic model of the semiotic system.

In applying the dyadic approach to sociotechnical systems, it was natural to focus on the coherence between the surface structure of the interface (i.e., the symbol or representation) and the responses or interpretations of the human operator. Research hypotheses in this paradigm were typically framed in terms of the coherence between general surface properties of the interface and the information processing demands. Classical examples include early work on shape coding to improve discriminability among different controls (Jenkins, 1947) and work on stimulus-response compatibility that looked at the coherence of the spatial topology of the display representation relative to the spatial topology of the response (Fitts & Seeger, 1953). More recently, attention has been given to the organization or clustering of information in the display (e.g., intergral versus separable displays), relative to hypothetical information processing limitations (e.g., parallel versus serial processing) (Wickens & Carswell, 1995). In all these instances, hypotheses about the relative effectiveness of alternative representations were often tested using generic tasks motivated by assumptions about the relevant information processes.

Peirce's Triadic Semiotic System

Peirce, the father of Pragmatism, was interested in the pragmatics of belief and action in the world. How is it that our beliefs about the world can become the basis for successful action in the world? Thus, Peirce brought a third component into the semiotic system. In essence, the third component reflects a source behind the sign or representation – i.e., a problem domain or a natural ecology. By adding this third component, Peirce brought two additional relations into the semiotic system. In addition, to the *coherence* between the sign and the expectations of the agent considered in the dyadic system, the triadic system involves the *structural mapping* between the sign and the source domain and the *correspondence* between the agent's beliefs about action and the actual consequences of action in that source domain as illustrated in Figure 2.

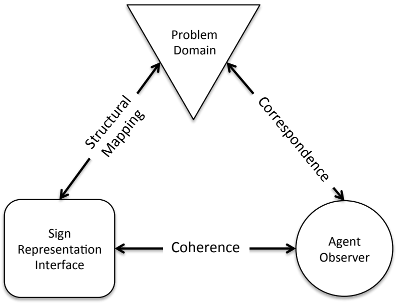

Figure 2. Peirce's triadic model of semiotics introduces a third 'body' into the system.

In the triadic model, the semiotic problem changes from interpreting a symbol to adapting to the demands of a problem domain. Rather than the symbol or representation being the 'stimulus,' it becomes simply a medium, with the stimulus displaced to the problem domain. The ultimate test of the triadic system is not whether the representations match the agent's expectations and beliefs, but rather whether the agent's expectations and beliefs support successful interactions with the problem domain. Attention shifts from the *syntax* of the surface features of the interface representation to the *semantics* associated with the deep structure of the problem domain. And the pragmatic design goal is to shape the agent's expectations through training and/or interface design in ways that lead to productive interactions with the problem domain.

Note that in the triadic semiotic system, the *USER-centered* concerns associated with the coherence between the interface and agent expectations remain an important component of the semiotic system. However, the triadic model also raises additional *USE-centered* concerns about the relations between structure in the representation and the functional constraints associated with the target problem domain (Flach & Dominguez, 1995). *In the context of the triadic model, the design challenge shifts from* *'matching' the agent's mental model, to 'shaping' the agent's mental model so that it supports productive action with regards to a target problem domain.*

The Three Body Problem

As physicists know, modeling the motion of interacting bodies in space becomes significantly less tractable when a third body is introduced. This is one of the major attractions of the dyadic approach to semiotics. Using the dyadic framework the image guiding research was that of a communication channel and problems of cognition were reduced to open-loop, symbol processing problems, constrained only by internal information processing limits as illustrated in Figure 3A. In this context, research questions became significantly more tractable in terms of identifying simple causal relations between stimuli and responses. This allowed the use of simple laboratory paradigms motivated by information processing models for independent stages of processing. The general stage specific tasks required no special knowledge so that general populations of readily accessible participants could be studied. Thus, large-N studies were feasible and it was possible to use strong statistical inference to judge effects.

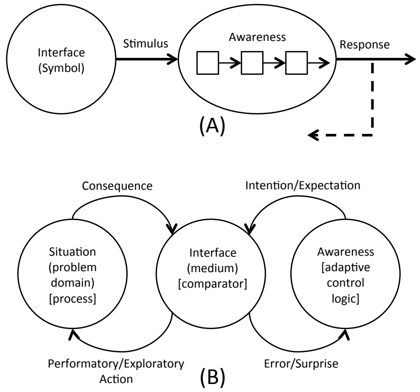

Figure 3. This diagram illustrates that introducing a third body changes the underlying dynamics from open-loop (i.e., causal) to a closed-loop (i.e., self-organizing).

In contrast to the communication channel metaphor, the triadic model of semiotics suggests a dynamic closed loop coupling between perception and action as illustrated in Figure 3B. This reflects an abductive logic where the 'tests' of beliefs are the practical consequences from acting on those beliefs. In this dynamic, the 'sign' interface has a dual function in terms of action/control (i.e., comparing the difference between consequences and intentions – *error*) and perception/observation (i.e., comparing the difference between consequences and expectations – *surprise*). This leads to a self-organizing dynamic where the cognitive agent is simultaneously shaping actions and being shaped by the ecological consequences of those actions. To understand the dynamics of the triadic system it becomes necessary to understand the constraints associated with the work domain or problems space (i.e., deep structure) and the potential interactions of these constraints with the internal constrains (i.e., mental models) of the human agents in relation to observation and control. In the following sub-sections some implications for approaching the triadic semiotic system are considered.

Cognitive Task versus Work Domain Analysis

As reflected in the images of the triadic semiotic system, a necessary step in a triadic approach is to bring the work ecology into the research frame. Thus, a prerequisite is to identify the deep structure of that ecology. This is the goal of Work Domain Analysis (WDA) (Vicente, 1999). To set the context for this, it is important to distinguish WDA from Cognitive Task Analysis (CTA) (e.g., Fleishman & Quaintance, 1984). CTA has typically been designed to reflect the information processing activities associated with the work. This makes perfect sense from the dyadic perspective where the focus was on cognitive activities inside the head of the human agent. In contrast, the focus of WDA is on the functional constraints associated with the problem domain. For example, in aviation this includes the aerodynamic constraints on vehicle motion, situational factors within the airspace (e.g., weather), the regulatory constraints on airspaces, as well as the value constraints against which safety and efficiency are measured. The goal is to better understand the 'deep structure' of the problem.

Representative Design of Experiments

Research motivated by the dyadic approach is often designed to isolate variables associated with specific internal information processing stages. Thus, the choices of tasks and independent variables are typically motivated by models of the internal stages. Even when the research is conducted within high fidelity simulations (e.g., a flight simulator), the research will often focus on secondary tasks (e.g., memory search or probe reaction time) that are thought to tap into the relevant internal mechanisms.

In a triadic approach, however, the focus is on how performance is shaped by the deep structure of the problem domain. Thus, the tasks and independent variables are explicitly chosen to reflect that deep structure. This requires that the evaluation context be *representative* of the work domain. It is important to appreciate that representativeness does not simply mean that the interface (e.g., knobs and dials) functions properly (e.g., as in a high fidelity flight simulation). It also involves the validity of the problem that is driving the interface – that is the dynamics of the problem context that the research is intended to generalize to. So, for example, the triadic approach requires the experimental *situations* or context are representative of the target domain. For example, in evaluating a design of new technologies for the next generation of air space management systems, it would be important that the evaluation contexts involve conditions that would be representative of future flight conditions (e.g., in terms of air traffic densities and regulatory constraints).

In addition to care in selecting the experimental task scenarios, it also becomes important to select participants from representative populations. For example, one cannot simply select a participant from an Introductory Psychology course and expect him to be able to fly a simulated aircraft under realistic air traffic conditions. Thus, the triadic approach demands care in selecting participants who have the appropriate skills and experience to address the problems presented. This raises the issue of competency.

Mission Essential Competencies

The construct of *Mission Essential Competencies* has emerged in the context of training applications and research (Alliger, Beard, Bennett, Colegrove, & Garrity, 2007). In contasting the dyadic and triadic approaches, the key distinction reflected in this construct is a shift from focusing on generic information constraints to focusing on "mission relevant" abilities, skills, experience, and knowledge. Thus, the construct of competencies focuses on the deep structure of work in terms of demands for success in a specific work domain. For example, with respect to air combat, Colegrove and Alliger (2002) define MEC as "higher-order individual, team, and inter-team competency that a fully prepared pilot, crew, flight operator, or team requires for successful mission completion under adverse conditions and in a non-permissive environment." In essence, constistent with the triadic approach, the MEC construct *situates* or grounds the properties of the cognitive agent (i.e., awareness) relative to specific demands of a work domain (i.e., situations) and this provides a triadic basis for making decisions for designing training scenarios and goals.

Ecological Interfaces

Training reflects one path for shaping the internal models of operators so that they better correspond with the deep structure of specific problem domains leading to more productive actions. Another means for shaping the internal models of operators is through the design of interface representations (Bennett & Flach, 2011; Rasmussen & Vicente, 1989). The construct of *Ecological*

Interface Design (EID) provides a triadic alternative to the conventional dyadic approach that tends to emphasize matching generic internal models (e.g., population stereotypes), rather than shaping internal models so that they better correspond with the demands of specific work domains. The emphasis of the EID approach is on designing display constraints (e.g., configural visual graphics) that are explicitly mapped to the underlying deep structures of the work domain. In this context, the emphasis shifts from focus on capacity limitations to skills such as chunking that allow experts to by-pass these limitations in order to meet the demands of complex tasks (e.g., Chase & Simon, 1973; Ericsson & Charness, 1994). For example, research on chess suggests that the ability of chess experts to remember board positions and to quickly focus on good alternative moves reflects a different way of chunking information. Novices focus on individual 'pieces' and experts focus on the spaces that the pieces are attacking (Reynolds, 1982). Thus, structure in configural graphics is designed to bias operators toward organizing (i.e., chunking) information in ways that support productive thinking or expertise.

Synthetic Task Environments

The previous section illustrated some of the ways that the addition of the third 'body' to the semiotic system changes the questions that become most interesting for researchers. The clear implication of this shift for research is that it becomes necessary to incorporate the deep structure of specific work domains into the experimental contexts. Fortunately, information technolgies such as high fidelity simulators and virtual environments provide one means to do this. These technologies allow researchers to build *synthetic enviroments* that represent the deep structures of specific work domains with a relatively high level of fidelity. While bringing more of the richness of natural work domains into the laboratory these synthetic environments offer possibilities for manipulation and replication of conditions that would not be possible in naturalistic settings. Additionally, these environments typically allow unobtrusive measurement of both the situation (i.e., independent variables) and operator performance (i.e., dependent variables) in ways that often are not possible in natural settings.

The Measurement Problem

The ability to simultaneously measure properties of the changing situation and the performance of operators at multiple levels of abstraction is both the biggest opportunity and the biggest challenge of synthetic task environments. On the opportunity side, one of the biggest challenges for conventional research focused on generic information processing tasks was to relate statistically significant differences observed in laboratory tasks to practical differences in specific work domains. Would a significant laboratory effect on reaction time translate to a practical difference in operational effectiveness? Synthetic task environments provide a means to address this question empirically. That is, within a synthetic task enviroment it is possible to simultaneously measure micro-level performance differences (e.g., reaction time to a specific display event) and more macro-level functional differences (e.g., winning or losing an engagement).

Comparisons across levels of abstraction provide empirical evidence about whether differences at the micro-level are correlated with success at the macro-level. Thus, questions about operational implications can be answered based on empirical evidence at the operational level and patterns between this evidence and other variables that might be more closely related to generic and specific constraints associated with internal mental models. Such measurement opportunities can provide a bridge between practice and theory that will lead to improvement on both ends. This bridge is particularly important for complex, nonlinear systems where analytical linear extrapolations fail, and insight typically depends on empirically linking quantitative changes at the micro-level with qualitative changes at the macro-level (e.g., Shaw, 1984).

The biggest challenge for research using synthetic task environments is data overload. The opportunity to measure everything, can make it harder to see anything. Based on my own experiences, I venture the guess that many research programs using synthetic task enviroments have oodles of data that get archived, but that are never analyzed or examined. In order to take advantage of the data that synthetic environments make available to researchers, it can be essential that the search of that data is guided by theories about the deep structure of the work domain, about the domain specific competencies required, and about the generic constraints on awareness. The three body problem is inherently intractable! Thus, solution depends on clever partitioning of the problem and the use of converging operations to discover and isolate signals (e.g., patterns associated with fundamental properties) that are embedded in the complexity.

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