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A cognitive prosthesis for complex decision-making

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ABSTRACT

While simple heuristics can be ecologically rational and effective in naturalistic decision making contexts, complex situations require analytical decision making strategies, hypothesis-testing and learning. Sub-optimal decision strategies – using simplified as opposed to analytic decision rules – have been reported in domains such as healthcare, military operational planning, and government policy making. We investigate the potential of a computational toolkit called "IMAGE" to improve decision-making by developing structural knowledge and increasing understanding of complex situations. IMAGE is tested within the context of a complex military convoy management task through (a) interactive simulations, and (b) visualization and knowledge representation capabilities. We assess the usefulness of two versions of IMAGE (desktop and immersive) compared to a baseline. Results suggest that the prosthesis helped analysts in making better decisions, but failed to increase their structural knowledge about the situation once the cognitive prosthesis is removed.

1. Introduction

It has been demonstrated on numerous occasions both in field studies and laboratory experiments that human decision-makers confronted with complex situations fail to perform satisfactorily despite their well-intended efforts (Funke and Frensch, 1995; Gonzalez et al., 2005; Osman, 2010a; Quesada et al., 2005; Yasarcan, 2010). Using computer-simulations of complex situations, Dörner (1996) noted particular examples of behaviors leading to successful performance (e.g., active learning and hypothesis testing) as well as numerous instances of poor behaviors leading to failure, which were generally linked to cognitive limitations and poor understanding and/or decision-making strategies (e.g., thinking in terms of isolated cause-and-effect relationships). Analysts and decision-makers confronted with complex situations could thus benefit from external support tools to help overcome cognitive limitations and facilitate broader situational understanding (e.g., interactive relationships, and projection of future consequences). The current study assesses whether IMAGE – one such cognitive prosthesis based on visual analytics – can augment analysts' structural knowledge and encourage optimal decision-making strategies.

Complex systems are characterized by uncertainty and non-linear interactions (Blech and Funke, 2005; Diehl and Sterman, 1995; Forrester, 1993) making it difficult to understand relations between elements. Furthermore, consequences of actions are often delayed in time and diluted by natural dynamic changes (Karakul and Qudrat-Ullah, 2008), while feedback may also be distorted, subject to misinterpretation, or imperceptible (Sterman, 2006). The dynamics of such systems are determined by their underlying structure, so knowledge about the causal relations between the elements comprising such systems – referred to as *structural knowledge* (Davis et al., 2003) – is critical for performing effective decision-making in this context (e.g., Blech and Funke, 2005; Gagnon et al., 2012). However, decision-making is not solely dependent on the quality of structural knowledge, as heuristics – simple but effective strategies that do not require a profound knowledge of a situation – may also be used and can often lead to good performance in certain task ecologies that favour the simplicity principle (Gigerenzer and Gaissmaier, 2011; Gigerenzer and Selten, 2001; Shah and Oppenheimer, 2008). Of course, not all task ecologies favour simple strategies. For example, many contemporary organizations are complex sociotechnical systems

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that require analytically-derived management guidelines (Righi and Saurin, 2015). While simple heuristics can be ecologically rational and effective in various naturalistic decision making contexts, it follows from Ashby's law of requisite variety (Ashby, 1968) that complex situations require analytical decision making strategies, hypothesis-testing and learning.

Heuristics may introduce biases that can lead to substandard decisions and failure of strategic decision-making in complex situations such as health care (e.g., Agyepong et al., 2012), military strategic decision-making (e.g., Cohen, 2012), foreign policy making (e.g., Mitchell and Massoud, 2009) and macro-economy (Stekler, 2007). When dealing with such complex systems, heuristics fail to integrate sufficient complexity, and often generate less than satisfying outcomes (Betsch et al., 1998; Betsch et al., 2001, 2004). The limitations associated with intuitive heuristics have been referred to as cognitive "pathologies" (Cooper, 2005; Heuer, 1999), with "pathological" behaviors including excessively reactive decision-making (focusing on fixing salient problems, i.e., a *fire-fighting* approach), lack of hypothesis testing, failure to consider potential side-effects or long-term effects of decisions, focusing on the present situation rather than on developmental trends, linearly projecting the situation into the future, searching for unique "one-factor" causes to problems, thematic vagabonding (focusing successively on different sub-problems with no coherent plan), and encystment (focusing on a single sub-problem) (Dörner, 1996). Decision-making quality may be helped by external tools that can support the development of structural knowledge rather than the use of heuristics.

1.1. Cognitive prostheses

Cognitive prostheses are tools designed to augment cognition by offloading part of the information processing or representation requirement onto external artifacts (Cooper, 2005; Heuer, 1999). External cognition refers to the use of (mainly visual) representations to (1) reduce cognitive effort (computational offloading), (2) make problem-solving easier by *re-representing* information in a more tractable form, and (3) guide inferential reasoning about the underlying situation using graphs (see Scaife and Rogers, 1996). Tools supporting external cognition may promote the use of more analytical reasoning techniques over simple heuristics (Arias-Hernandez et al., 2012), or help overcome cognitive bounds such as data overload and confirmation bias (Heuer, 1999; Johnston, 2005).

1.2. IMAGE – A cognitive prosthesis

The IMAGE system (Lizotte et al., 2012) – so named to reflect its emphasis on visual representation – is a set of advanced visual analytics technologies to help improve analysts' understanding of complex situations by fostering the use of analytical reasoning strategies. IMAGE provides the user with added computational resources designed to support the adoption of "stronger" analytical methods of reasoning as opposed to "weaker" intuitive methods (see Bryant et al., 2003). In order to achieve this goal, IMAGE provides three functions: (1) interactive simulations for hypothesis testing, (2) enhanced visualizations and (3) knowledge representation. Together, these functions allow the user to experiment with a simulation model to better understand a complex situation's dynamics. The user can manipulate the situation parameters and potential decisions in different simulation runs to observe the different outcomes. The user then attempts to discover trends, tipping points, and trade-offs using the interactive visualizations. Finally, the user captures his insights and his understanding of the complex situation in the knowledge representation component. This knowledge discovery process is not expected to operate in a linear sequential fashion, but rather as a series of iterations going back and forth across these different components.

1.2.1. Interactive simulation

When acquiring structural knowledge, "direct" learning involving active interaction with the environment may be more effective in complex settings than (vicarious) learning by observing the interventions of others – i.e., indirect learning about the environment (Lagnado and Sloman, 2004; Osman, 2010b). Indeed, cognitive studies examining causal learning processes suggest that structural knowledge is more accurate when one can influence and interact with potential causes rather than merely observe causes and their effects (Lagnado and Sloman, 2004; Steyvers et al., 2003). Interventions are important for causal learning in the sense that they enable the differentiation of compatible causal structures through hypothesis testing (Hagmayer et al., 2007).

The interactive simulation module of IMAGE (called Multichronia) runs a computational model of a complex situation and allows the analyst to interact with this model by creating "what-if" simulations and manipulating key parameters (Lizotte et al., 2012; Rioux et al., 2008). When interacting with the computational model using Multichronia, three types of actions are possible: Creating a simulation instance with new initial conditions; changing the value of a parameter at one point in time; and creating diverging simulation branches at different points in time (forming a multichronic tree, see Fig. 1) to observe the impacts of different parameters on various measures of performance (MoP). For the purpose of the experiment described below, the parameters of each simulation had to be specified by the analyst. Consequently, it was not possible to simulate the model in "batch-run" mode, thus ensuring that analysts would interact with the simulation model and actively engage in hypothesis testing.

1.2.2. Enhanced visualizations

Visualization is used for various functionalities such as data aggregation (e.g., Kandel et al., 2012), coordinating multiple views, and linking different sets of data to assess relationships between dimensions (e.g., González-Torres et al., 2013). Visually representing pre-processed data allows analysts to infer relationships or detect patterns without being constrained by cognitive limits such as the bottleneck of short-term memory (Thomas and Cook, 2005, 2006). This has been shown to improve performance in a wide variety of contexts including bioinformatics (Baehrecke et al., 2004), medicine (Tominski et al., 2008), databases (Shneiderman, 2008), and e-Learning (Aguilar et al., 2009). Furthermore, visualizations can be improved by employing immersive virtual environments (Van Dam et al., 2000) such as a Cave automatic virtual environment (CAVE; Cruz-Neira et al., 1992; Demiralp et al., 2003). A CAVE typically comprises three to six projectors arranged to display data on the walls of a room-sized cube, creating an environment that surrounds the user and provides a sense of immersion. Immersive tools can improve the identification of data clusters (Arms et al., 1999), as well as simple and complex searches (Laha et al., 2012). Such benefits of immersive virtual environments are partly explained by increased "presence" – an increased task focus resulting from the feeling of "being there" (Nash et al., 2000) – which is assumed to lead to a more sustained allocation of attentional resources and in turn, improved performance. However, the question remains as to whether a greater "presence" and more focused attention is sufficient to improve the understanding of complex situations.

IMAGE offers a toolbox of enhanced visualizations (Girardin, 2012; Lizotte et al., 2012; Mokhtari et al., 2013; Tye-Gingras, 2011), developed using Eye-Sys software (IDV inc.) that provides