Augmenting Cognition in Complex Situation Management: Projection of Outcomes Improves Strategy Efficiency

Daniel Lafond, Michel B. DuCharme, Marie-Ève St-Louis, and Sébastien Tremblay

***Abstract*—We investigated the effects of a decision aid designed to support the development of effective long term strategies when seeking to influence a complex adaptive system. The experiment compared a test condition with feedforward support (i.e., outcome projection) against a baseline condition both in terms of cognitive processing and goal attainment (i.e., strategy efficiency). Results show that the decision aid significantly improved the development of effective long term strategies, yet detracted participants from engaging in information acquisition behaviors. In both conditions, participants displayed a poor (unaided) ability to anticipate the system's near term behavior, which was significantly lower in the decision aid condition. Goal attainment was positively related to frequency and comprehensiveness of information acquisition, Level 3 situation awareness (near term projection), and the degree to which the participants' strategies were proactive. The decision aid therefore clearly helped overcome a serious limitation in human processing abilities in terms of outcome projection (thus helping participants develop better strategies). However, results show that decision aids may also come with certain drawbacks that need to be systematically identified and mitigated to obtain the full benefits of cognitive support technology.**

***Index Terms*—Cognitive support, complex system, decision making, simulation, situation management.**

I. Introduction

Decision makers in critical areas such as national defense, security, health care and environmental management face the daunting task of influencing a complex dynamic system of systems [1]-[2]. Unfortunately, complex systems tend to overwhelm the cognitive capabilities of decision makers, often leading to a phenomenon called tunnel vision [3]. Tunnel vision is defined as insufficient problem formulation and situation assessment, producing narrow-minded interventions that may lead to failure or even to the emergence of new unintended problems. Previous research has also shown that when dealing with complex systems, focusing on short term gains can be detrimental to the attainment of long term goals and that this may be one of the key reasons for human failure in such situations [4]-[5]. Conversely, taking a comprehensive and long term approach to deal more effectively with complex problems can be excessively challenging without cognitive support [1]. One way to provide cognitive support is to use an approximate model of the system with the means to derive plausible outcomes (i.e., feedforward) for a specific intervention or series of decisions, effectively enabling "what-if" reasoning during strategy development [6]-[7]. Indeed, such an approach amounts to supporting situation awareness (SA) in terms of the projection of future outcomes. Situation awareness is conceptualized as combining the perception of elements in the environment within a volume of space and time (Level 1), the comprehension of their meaning (Level 2) and the projection of their status in the near future (Level 3) [8]. Arguably, decision support technology has the potential to extend human reasoning capabilities beyond proximal outcomes, leading to a hypothetical level 4 SA (long term projection), which may be critical for success in complex domains. Yet surprisingly, [9] have found that this type of feedforward support does not systematically lead to improved goal attainment. This form of cognitive support thus deserves further investigation on its factors of success and failure.

Here, we report the results of an experiment investigating the impact of a decision aid on the information acquisition and decision making behaviors of human participants in a simulated society management game called Ecopolicy (MCB-Verlag). The experiment applies an objective measure of Level 3 SA conceived for the present study. Ecopolicy was designed to educate people about the importance of "networked thinking", i.e., striving to understand how variables interrelate when dealing with complex systems [6]. Indeed, a particularly striking aspect of this game is that even though the causes and effects within the system are clearly shown, people have a great difficulty bringing the system to the targeted state. They fail to understand the longer term

Manuscript received October 22, 2010. This work was funded by the Department of National Defence of Canada (ARP 10bp01), and supported by a postdoctoral research fellowship to D. Lafond from the Department of National Defence of Canada.

D. Lafond is with Defence R&D Canada, Québec, QC, G3J 1X5, Canada (e-mail: daniel.lafond@drdc-rddc.gc.ca).

M. B. DuCharme is with Defence R&D Canada, Québec, QC, G3J 1X5, Canada (phone: 418-844-4000 x4224; fax: 418-844-4538; e-mail: michel.ducharme@drdc-rddc.gc.ca).

M.-È. St-Louis is with École de psychologie, Université Laval, Québec, QC, G1V 0A6, Canada (e-mail: marie-eve.st-louis.3@ulaval.ca).

S. Tremblay is with École de psychologie, Université Laval, Québec, QC, G1V 0A6, Canada (e-mail: sebastien.tremblay@psy.ulaval.ca).

implications of their decisions and the system clearly demonstrates "policy resistance" [10], when interventions turn out to have the opposite of the intended effect. This strategy game shows the pitfalls of focusing on isolated problems without carefully considering the whole set of interactions within the system. Two types of knowledge are generally viewed as critical for effective decision making in a complex environment: structural knowledge and strategic knowledge [11]. Structural knowledge refers to the understanding of the causal relationships within the system. It is typically measured by eliciting a schematic representation of the participants' mental model of the system or assessing its accuracy using test questions [12]. Structural knowledge is essential for achieving accurate Level 2 and Level 3 SA. Strategic knowledge is defined here as the set of lessons learned, rules, priorities and tactics that help the decision maker devise an effective course of action to reach a set of goals. In Ecopolicy, participants can acquire structural knowledge by accessing information about the cause-effect relationships in the system using an interactive influence diagram (see Fig. 1). The development of strategic knowledge can be supported by providing feedforward support (i.e., outcome projection) using a decision aid we designed for Ecopolicy. The main goal of the experiment reported here is to compare a condition with cognitive support against a baseline condition in terms of information acquisition behaviors, in terms of situation awareness (based on an objective measure of Level 3 SA) and in terms of goal attainment (i.e., strategy efficiency). Our main hypothesis is that the decision aid, by helping foresee future problems, will stimulate information acquisition behaviors (learning) to understand how these problems arise, therefore improving Level 3 SA and the development of effective courses of action.

II. METHOD

A. Participants

Forty participants (mean age: 23.8 y) from a wide variety of backgrounds (mainly Social Sciences and Engineering), including 22 men and 18 women, received a $40 compensation for their participation in two 2-hour experimental sessions. Participants were randomly assigned to either the test or baseline condition (i.e., with or without the decision aid).

B. Apparatus

The experiment is run on a standard personal computer with two flat screen monitors. The Screen 1 displays the Ecopolicy interface and Screen 2 displays an interactive Microsoft Excel file used for measuring Level 3 SA and for interacting with the decision aid.

In Ecopolicy, participants are in charge of managing a country for twelve simulated years (or game-turns), by allocating "activity points" in one of four areas that can be influenced directly: sanitation, production, education, or quality of life. The state of the situation in a given year is described through eight variables that typically range from 0 to 30: Politics, Sanitation, Production, Environmental stress, Education, Quality of life, Growth rate, and Population. In the simulation, these eight dimensions mutually influence each other so that each decision results in a chain of effects within the system. Each year, the participant receives a number of additional activity points that depend on the current state of the society. Depending on its current value, each variable can be in a desirable or undesirable state as described by a five-color scale that goes from green to red. The goal of the participant is to bring all eight dimensions within the green zone by Turn 12. If a dimension goes too far in the "red" zone, the current government is overthrown and the game ends. The goals are i) to maximize the value for Politics, Sanitation, Education and Quality of life; ii) to minimize Environmental stress; and iii) to keep Production, Growth rate and Population in the middle range of the scale. Fig. 1 illustrates the main Ecopolicy interface and the interactions between system variables. The functional relationship between two variables can be viewed by clicking on a specific interaction.

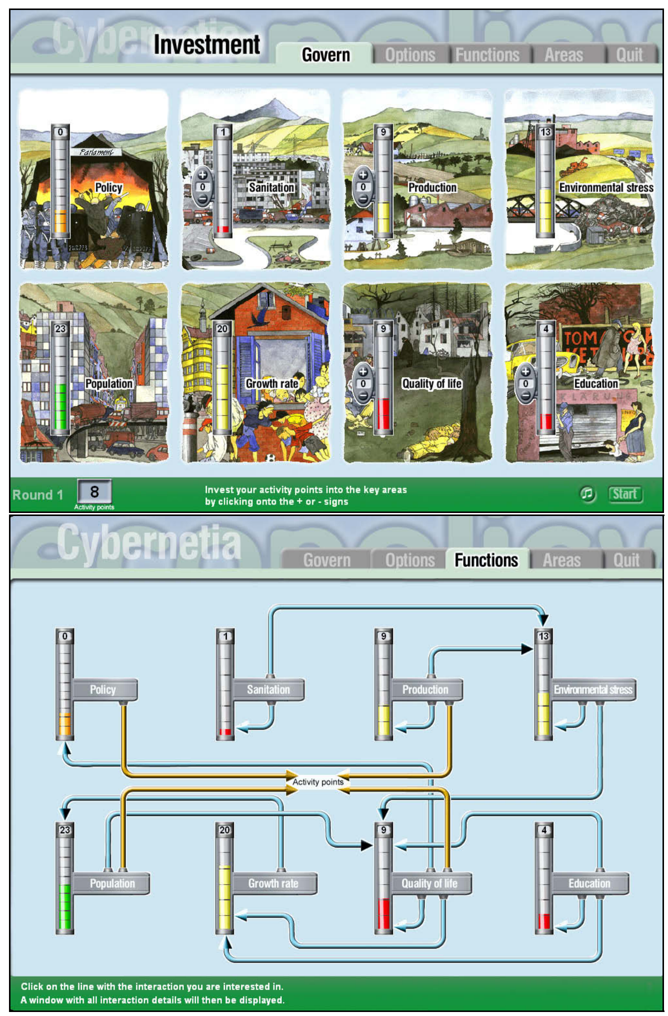

Fig. 1. The Ecopolicy interface and the 18 cause-effect relations. Clicking on an arrow reveals the detailed interaction

The computational decision aid provided in the test condition extrapolates the likely outcomes of a series of decisions entered by the participant (i.e., the participant's current plan for the present and upcoming turns). Participants can consider different courses of action and learn from the anticipatory feedback (i.e., feedforward) provided by the decision aid (thus supporting the development of strategic knowledge). For realism's sake, some noise is added to those projections (to prevent participants from having a perfect "crystal ball"). More precisely, 50% of the projections are slightly higher or lower that the actual outcome. Yet the effect of noise is also cumulative, thus creating an increasing degree of uncertainty about future turns. The presence of noise also ensures that participants need to revise their plan on each turn since the outcomes are not exactly those projected by the tool.

C. Procedure

The experiment involves a tutorial and 6-turn practice session and a 12-turn test session followed by a short questionnaire. The simulation has a different starting state in the practice phase and the test phase (i.e., the initial value of the eight variables is different). On each game-turn, participants are first presented with the Level 3 SA measure (described below) on Screen 2. Then, participants may decide how they wish to allocate their activity points to influence the system. Those in the test condition may use the decision aid at their leisure before entering their decision for the current turn. There is no time-limit for each turn. Participants can inspect the cause-effect relationships in the system (graphic display and text description of these effects) via the Functions tab in Ecopolicy. Feedback on the changes occurring in the society is provided during the transition from one game-year to the next. The game ends after one of three events occurs: i) the society has reached the target state for all 8 dimensions, ii) 12 years have passed, or iii) the government has been overthrown.

D. Measures

Goal attainment. The score at the end of the game is based on the relative distance of the eight dimensions of the society to the nearest "green value" multiplied by the proportion of the mandate completed (i.e., all else being equal, those who survive longer are thus considered more effective), resulting in a scale ranging from 0 to 100.

Information acquisition. Providing participants with information on the cause-effect relationships in the system does not guarantee that participants actually acquire and understand that information. Information acquisition frequency was defined as the number of times participants requested information about the interrelationships between system variables. The average proportion of the system inspected throughout the duration of the game indicated the degree of comprehensiveness of information acquisition.

Level 3 SA (understanding of proximal outcomes). We measured the (unaided) ability of participants in both groups to consider the mutual influences (and time-delays) between system variables in an integrated manner in order to anticipate the outcome of these interactions for the following game-turn. For each year in the game, we record the eight predicted values and the eight correct values that describe the state of the society in the subsequent year. Each prediction for a specific dimension of the society is a discrete number between 0 and 30. We then compare the change in the situation predicted by the participant for each variable to the correct response. The score for a given participant corresponds to the coefficient of determination, referred to as the "proportion of variance accounted for" (PVAF) by the participant:

$$PVAF = \frac{\text{Total variation - unexplained variation}}{\text{Total variation}} \quad (1)$$

$$PVAF = \frac{\sum (Y-\bar{Y})^2 - \sum (Y-\hat{Y})^2}{\sum (Y-\bar{Y})^2} \quad (2)$$

where Y is the correct prediction, $\bar{Y}$ is the average value of Y and $\hat{Y}$ is the participant's prediction.

Decision strategy questionnaire. The post-experimental questionnaire required participants to perform self-evaluations of the overall decision making strategy they used during the game (using a five-point Likert scale) along five dimensions: focalized vs. integrative, short vs. long term, reactive vs. proactive, intuitive vs. analytic, simple vs. elaborate.

III. RESULTS

A. Goal attainment

A *t*-test comparing goal attainment across the two groups showed that the participants in the decision aid condition (M = 73.3%, SD = 28.9) obtained higher scores than the baseline condition (M = 43.3%, SD = 21.4), $t(38) = 3.73$, $p = .001$.

B. Information acquisition

The average frequency of information acquisition behaviors per turn was lower in the decision aid condition (M = 7.0, SD = 8.4) compared to the baseline condition (M = 15.1, SD = 14.3), $t(38) = 2.164$, $p = .037$. However, the comprehensive-ness of information seeking behaviors was not significantly different across conditions, $t(38)$, 1.348, $p = .186$.

C. Level 3 SA

The understanding of proximal outcomes of the situation (Level 3 SA) was lower in the decision aid group compared to the baseline group in all turns but one (Turn 8), yet the overall average did not significantly differ across groups due to the high variability in the data, $t(38) = 1.388$, $p = .173$. It seemed important to investigate this trend further, so we reduced the scope of the analysis. The excessive variability was mainly observed for the late turns and seems clearly related to the considerably reduced sample (i.e., 30% to 45% attrition from Turn 7 to Turn 12). Turn 1 was also excluded since the decision aid was not yet presented and both conditions were basically identical at this point. This more focused analysis shows that Level 3 SA was significantly lower in the decision aid condition (M = .17, SD = .21) compared to the control group (M = .33, SD = .28), $t(38) = -2.064$, $p = .046$.

D. *Decision strategy questionnaire*

A significant difference between groups was found for the short vs. long term dimension of the questionnaire, with the decision aid condition being more oriented toward a long term strategy (M = 3.9, SD = 1.0) compared to the baseline condition (M = 3.0, SD = 1.3), $t(38) = 2.538$, $p = .015$. No significant difference was found for the other dimensions.

E. *Partial correlations*

Partial correlations on the complete sample of participants indicate the degree of association between key variables while controlling for the group effect. Goal attainment was found to correlate positively to comprehensiveness of information acquisition ($r = .49$, $p = .002$), Level 3 SA ($r = .37$, $p = .024$), and the degree to which the participants' strategies were proactive as opposed to reactive ($r = .46$, $p = .004$). Level 3 SA was found to be positively associated to the information acquisition frequency ($r = .53$, $p = .001$) and comprehensiveness ($r = .80$, $p < .001$) and to the use of a more analytical (as opposed to intuitive) decision strategy ($r = .44$, $p = .006$).

IV. Discussion

As hypothesized, the decision aid clearly improved the development of more effective long term strategies, yet it appears to have detracted participants from engaging in information acquisition behaviors (i.e., reduced frequency). Participants displayed a poor understanding of the system's behavior (i.e., low Level 3 SA) in both conditions, yet contrary to our hypothesis, results were significantly lower in the decision aid condition. Although the decision aid helped overcome a serious limitation in human processing abilities in terms of outcome projection (thus helping participants develop better strategies), it also came with a drawback. Participants in the decision aid condition, while focusing more on long term strategic analysis/planning, acquired less structural knowledge, thus leading to a reduced ability to accurately project short term outcomes compared to the baseline condition. By teaming up with a tool to improve effectiveness, the human component of this joint cognitive system naturally adapted its sensemaking process and delegated part of the cognitive work to the computational component [13]. When evaluating the impact of cognitive support, assessing cognitive functioning as a whole rather that just the targeted function can help ensure that other essential functions are not unintentionally impaired [14].

A more general analysis, based on partial correlations on the complete sample of participants (controlling for the group effect) showed that goal attainment was positively related to comprehensiveness of information acquisition, Level 3 SA, and the degree to which the participants' strategies were proactive (as opposed to reactive). Finally Level 3 SA was positively associated to both measures of information acquisition (arguably, structural knowledge is a key prerequisite for Level 2 and Level 3 SA) and to more analytical decision strategies. These findings show that many measurable characteristics associated to the general concept of tunnel vision (infrequent and incomplete information acquisition, lack of analysis), are indeed closely related to poor decision-making. Training participants to avoid those behaviors associated with tunnel vision may constitute an effective way to improve complex decision making ability.

In many complex situations, situational information is incomplete, the possibility to acquire structural knowledge is rather limited, and modeling may not provide very accurate predictions. Under these particularly challenging conditions, the need for better cognitive engineering and methods to deal effectively with high levels of uncertainty becomes of utmost importance. One approach put forward by the sensemaking support tool called the Sensitivity Model – from which the Ecopolicy game was derived – relies on fuzzy logic to facilitate the incorporation of "soft" (i.e., hard to quantify) factors into the models developed by the user [6]. Another key approach being put forward pertains to robust decision making [15]-[16] which relies heavily on computational support for managing risks and uncertainty (to identify robust rather than optimal solutions) and shows great promise to help decision makers adapt to this challenging reality.

Acknowledgment

Thanks are due to Jean-François Gagnon and Bernard Lebel for their valuable comments and assistance in preparing the experiment, data collection, and data analysis.

References

[1] D. Dörner, *The logic of failure: Recognizing and avoiding error in complex situations*. Reading, MA: Addison-Wesley. 1996.

[2] Horn, B., "Complexity squared: operating in the future battlespace," *Canadian Military Journal*, Autumn, pp. 7-15. 2003.

[3] A. Miller, "Tunnel Vision in Environmental Management," *The Environmentalist*, vol. 2, pp. 223-231. 1982.

[4] T. Gureckis and B. Love, "Short-term gains, long-term pains: How cues about state aid learning in dynamic environments," *Cognition*, vol. 113, pp. 293-313. 2009.

[5] D. Lafond, M. B. DuCharme, J.-F. Gagnon, and S. Tremblay, "Cognitive support requirements for decision making in complex systems," *9th Asia-Pacif. Comp. Sys. Conf.,* Tokyo, JP, Nov. 4-7. 2009.

[6] F. Vester, *The art of interconnected thinking: Ideas and tools for tackling with complexity*. MCB: Verlag. 2007.

[7] M. Lizotte, F. Bernier, M. Mokhtari, E. Boivin, M. B. DuCharme, and D. Poussart, "Image: Simulation for understanding complex situations and increasing future force agility," *The 26th Army Science Conference*, Dec. 1-4, Orlando, FL. 2008.

[8] M. R. Endsley, "Situation awareness global assessment technique (SAGAT)," *in Proc. of the National Aerospace and electronics conference*. New York: IEEE, pp. 789–795, 1988.

[9] F. J. Lerch, and D. E. Harter, "Cognitive support for real-time dynamic decision making," *Info. Sys. Res.*, vol. 12, pp. 63–82. 2001.

[10] J. D. Sterman, "Learning from evidence in a complex world," *American Journal of Public health*, vol. 96, pp. 505-514. 2006.

[11] W. Schoppek "Examples, rules, and strategies in the control of dynamic systems," *Cognitive Science Quarterly*, vol. 2, pp. 63-92. 2002.

[12] J. K. Doyle, and D. N. Ford, "Mental models concepts for system dynamics research," *Sys. Dyn. Rev.,* vol. 14, pp. 3-29. 1998.

[13] D.D. Woods and E. Hollnagel, *Joint cognitive systems: Patterns in cognitive systems engineering*. Boca Raton, FL: CRC Press, 2006.

[14] D. Lafond, F. Vachon, R. Rousseau, and S. Tremblay, "A cognitive and holistic approach to developing metrics for decision support in command and control," in D. Kaber & G. Boy (Eds.), *Advances in Cognitive Ergonomics* (pp.65-75). Boca Raton, FL: CRC Press. 2010.

[15] G. L. Klein, M. Pfaff, and J. L. Drury, "Supporting a robust decision space," in *Proc. of the AAAI Spring Symposium on Technosocial Predictive Analytics*, Stanford, CA, March. 2009.

[16] B. Chandrasekaran and M. Goldman, "Exploring robustness of plans for simulation-based course of action planning," in *Proc. IEEE Symp. on Comp. Intel. in Multicrit. Decis. Making*, Honolulu, HI, April. 2007.