Cognitive Support Requirements for Decision Making in Complex Systems

Daniel Lafond[1], Michel B. DuCharme[1], Jean-François Gagnon[2], Sébastien Tremblay[2]
[1]Defence R&D Canada – Valcartier, [2]Université Laval, Québec, QC, Canada

ABSTRACT

The present paper reports an experiment studying the cognitive functions required for effective decision making in a complex and dynamic environment. In particular, we studied the effects of anticipating the consequences of a decision and of strategy elaboration. Participants performed a simulated society management task in one of three conditions: i) a baseline condition, ii) a condition that requires participants to anticipate the outcomes of their decisions, or iii) a condition that provides a decision aid which automates the anticipation function. The degree of strategy elaboration was measured using a post-experimental questionnaire. Participants performed comparably in the three conditions. However, we found that in the two anticipation conditions there was a significant positive correlation between the degree of strategy elaboration and task performance. Our analysis suggests that two cognitive functions may be *jointly* necessary for effective decision making in a complex and dynamic environment: anticipation (integration and application of structural knowledge), and strategy elaboration (identification of sub-goals based on system understanding).

Keywords: complex system; decision making; cognitive support; anticipation, strategy

INTRODUCTION

Planners and decision makers in military command and control, designers of complex socio-technical systems and strategic policy makers all depend on their capability to understand and anticipate the behaviour of complex dynamic systems (Burnett, Wooding, & Prekop, 2005; DeLaurentis & Callaway, 2004; Horn, 2003). Understanding the dynamics of a complex system or organization can help foresee the side effects of a decision, adapt to events before they occur and influence system behaviour more effectively. Comprehension is defined here as the product of sensemaking: a motivated, continuous effort to understand information or a situation in order to anticipate its trajectory and act effectively (Klein, Moon, & Hoffman, 2006).

It has been shown that human reasoning about complex dynamic systems is limited by the computational capabilities of the brain, though technology, training and teamwork may augment these capabilities (Halford, Baker, McCredden, & Bain, 2005; Karakul, & Qudrat-Ullah, 2008). According to many researchers and practitioners, there has been significant progress over the last decade in developing technologies and methods that support human sensemaking and decision making processes in complex domains (e.g., Allen, Corpac, & Frisbie, 2006; Busemeyer & Pleskac, 2009; Langton & Das, 2007; Lizotte, Bernier, Mokhtari, Boivin, DuCharme, & Poussart, 2008). Nonetheless, a better understanding of human cognitive requirements when faced with complex problems is needed to guide the development and evaluation of the technologies and methods in the cognitive support toolbox.

In the present study we wish to highlight the role of two specific macro-cognitive functions in a complex decision making environment: anticipation and strategy elaboration. The ability to project the state of the environment in the near future and to anticipate the near-term consequences of a decision is assumed to allow individuals to select appropriate courses of action in order to meet their objectives. Furthermore, we argue that anticipation accuracy constitutes a useful measure of system comprehension. Second, we propose that strategy elaboration, which involves identifying sub-goals and long-term planning, is another key cognitive function for decision making in a complex environment. The experiment thus aims measure the effects of an extrapolation tool designed to accurately perform the anticipation function.

Given that humans have difficulty to anticipate the proximal evolution of the system and fail to understand the immediate effects of their own decisions due to basic computational limits of working memory (Newell & Simon, 1972), we hypothesize that a tool that extrapolates these dynamic effects should help evaluate decisions and revise them before committing to a specific intervention. This may not solve the problem of having to develop an appropriate strategy involving multiple decisions over time but it may provide valuable help to cope with the complexity of the system. We also test whether simply emphasizing anticipation (by virtue of asking participants the anticipated outcome) proves helpful for decision making compared to a baseline condition without the anticipation measure.

The task is based on a German educational computer game entitled Ecopolicy (MCB-Verlag). Ecopolicy is a society management game that aims to educate people about the importance of "networked thinking", i.e., striving to understand how variables interrelate when dealing with complex systems (Vester, 2007). 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 implications of their decisions and the system clearly demonstrates "policy resistance" (Sterman, 2006), 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. A key difference with the classic studies by Dörner (1996) is that Ecopolicy provides structural knowledge about the system (cause and effect relations are provided to the decision makers), yet the task still proves to be a considerable challenge for most individuals.

METHOD

Participants. Thirty university students (mean age: 22.4 y) from a wide variety of backgrounds (mainly Social Sciences and Engineering), 11 men and 19 women, reporting normal or corrected-to-normal vision and normal hearing received $15 compensation for their participation. Participants were randomly assigned to one of three groups. Group 1 is the baseline condition. Group 2 and 3 participants are required to predict the short-term effects of their decisions. Group 3 benefits from a computer program that correctly extrapolates the short-term outcomes of a decision. In Group 3, participants are asked to anticipate the state of the next game-year before using the extrapolation tool.

Apparatus. The experiment is run on a standard personal computer with two flat screen monitors. The first monitor displays the Ecopolicy interface and the second monitor displays an interactive Microsoft Excel file that prompts the user for predictions and confidence ratings for these predictions and then presents the extrapolation tool. The MORAE software (TechSmith) logs all user interactions with input devices (keyboard, mouse) and records the information displayed on each of the two monitors.

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 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 Year 12. If a dimension goes too far in the "red" zone, the current government is overthrown and the game ends. The goal is (a) to maximize the value for Politics, Sanitation, Education and Quality of life; (b) to minimize Environmental stress; and (c) to keep Production, Growth rate and Population in the middle range of the scale. Figure 1 illustrates the main Ecopolicy interface.

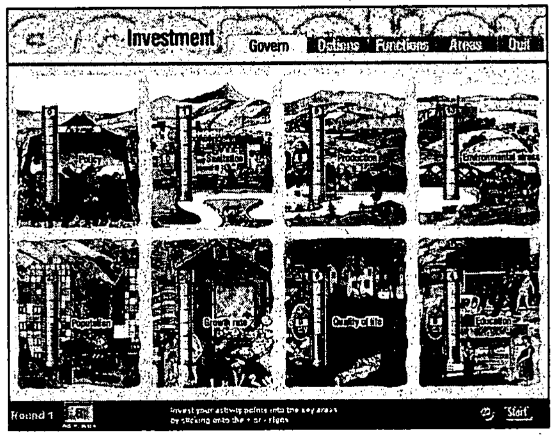

Figure 1. Ecopolicy interface

Figure 2 shows the interactions between system variables. The functional relationship between two variables can be viewed by clicking of a specific interaction.

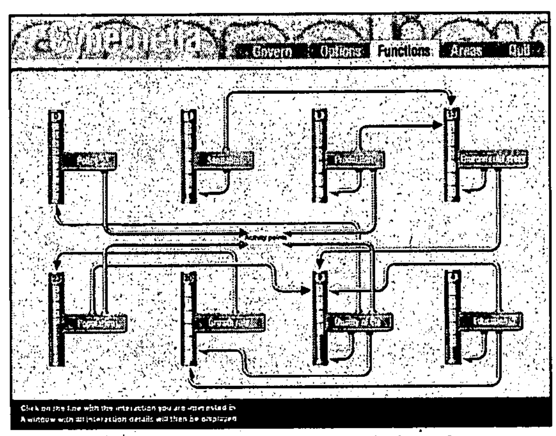

Figure 2. The 18 cause-effect relations between the society's dimensions in Ecopolicy. Clicking on a specific arrow reveals the detailed interaction

The extrapolation tool made available to a subset of participants (Group 3) implements the cause and effect relations (available to all participants in the *Functions* panel) and provides the user with an accurate extrapolation of the effects of the participant's decisions for the next game-year. The participant must first enter the eight variables of the current situation (and the number of activity points available) and then enter his decision in the Excel file. The decision aid instantly calculates the outcomes of that decision for the next game-year. Participants can therefore see the effects of taking no action and the effects of various interventions before making a final decision.

Design and Procedure. The anticipation measure consists of asking the participant to infer the state of the society for the next year. Each prediction is a discrete number (from 0-30) for a specific dimension of the society. The anticipation score for a given participant corresponds to the average sum of squared errors (SSE) between the eight predicted values and the eight correct values for each game-year. Lower SSE values correspond to a greater anticipation accuracy.

The game ends after one of three events occurs: i) the society has reached the target state for each of the eight dimensions, ii) 12 years have passed, or iii) the government has been overthrown. The score at the end of the game (i.e., performance or goal achievement) is calculated as follows: For each dimension of the society, a score of 1, 2, 3, 4 or 5 is assigned depending on the value range (from red to green). The eight numbers are added together and the score is then converted to a scale ranging from 0-100. Finally, if the government is overthrown before the end of year 12, the score is multiplied by the proportion of the 12-year mandated that was completed.

Participants underwent the following test procedure during a single visit in a research laboratory at Université Laval. The session began with a 15-min tutorial on how to play the game (Groups 1-3), how to generate predictions (Groups 2-3) and how to use the extrapolation tool (Group 3). Participants were instructed that it is very important to inspect all 18 cause-effect relations between the society's dimensions and develop a good strategy prior to the first decision. After entering a decision, participants entered their predictions of the future state of the eight variables (and a confidence-rating in those predictions) in the Excel file displayed on the second monitor (Groups 2 and 3). Then, participants in Group 3 could use the extrapolation tool to observe the actual effects of their decision, consider other options and if desired, change their decision (note that the anticipation measure was based on the initial decision and predictions could not be changed at this point). Finally, participants were asked to write down a description of the strategy they used during the task. They were also asked to rate on a scale from 0 to 4 to what extent they considered the anticipation phase and the extrapolation tool helpful for accomplishing the task. There was no time limit to accomplish the task.

RESULTS

Game duration. An analysis of variance of the number of game-years completed for Group 1 (M = 6.7, SD = 3.83), Group 2 (M = 6.9, SD = 3.9) and Group 3 (M = 7.6, SD = 2.5) showed no significant difference, $F(2,27) = .185$, n.s. The average decision making time (in seconds) for each game-year for Group 1 (M = 201.73, SD = 110.52), Group 2 (M = 388.52, SD = 281.59) and Group 3 (M = 417.28, SD = 277.58) was also not significantly different, $F(2,27) = 2.44$, n.s. This decision-time measure is essentially descriptive however since it does not exclude the additional time required by the anticipation measure (Groups 2 and 3) and the time spent interacting with the extrapolation tool (Group 3).

Performance. An analysis of variance showed no significant difference in the score of participants between Group 1 (M = 39.6, SD = 33.9), Group 2 (M = 42.9, SD = 35.2) and Group 3 (M = 41.1, SD = 22.3), $F(2,27) = .028$, n.s. Focusing on (short-term) anticipation or providing a tool that yields correct (short-term) predictions therefore did not help participants succeed in the task. This counterintuitive result actually highlights a key characteristic of complex systems called policy resistance (Sterman, 2006). Policy resistance means that interventions intended to have a specific effect in the short term generally fail to have the desired effect in the long term.

Anticipation. Participants in Group 2 and Group 3 did not significantly differ in terms of anticipation accuracy, $t(18) = .678$, n.s., and confidence ratings in their predictions, $t(18) = -.285$, n.s. We found no significant correlation between anticipation accuracy and the score of participants for Group 2 ($r = -.330$, n.s.) and Group 3 ($r = .244$, n.s.). Again, it appears that long term rather than short term considerations may be of critical importance in this complex system.

Helpfulness ratings. Participants gave an average helpfulness rating of 2.4 out of 4 to the anticipation phase. This result was not significantly different from a random distribution of responses as defined by a test value of 2.5 which lies at the middle point of the 0-4 scale, $t(18) = -.382$, n.s. Group 3 did consider the extrapolation tool helpful, with an average rating of 3.2 out of 4, which was significantly different from a random distribution of responses, $t(9) = 2.806$, $p < .05$. This result is clearly at odds with the fact that the extrapolation tool did not provide an advantage in terms of long-term goal achievement. Indeed, it is well-known that subjective evaluations are prone to biases (e.g. Poulton, 1989).

Strategy elaboration. The degree of elaboration of the strategies reported by participants was assessed by two judges who were well-acquainted with the task. The final measure was based on the average rating of the two judges. The ratings indicated the number of distinct sub-goals and constraints (e.g., things to avoid) expressed in the written strategy. The inter-judge correlation was very good ($r = .92$). A significant positive correlation was found between the degree of strategy elaboration and the final score for Group 2 ($r = .976$, $p < .001$), and Group 3 ($r = .615$, $p < 0.05$, unilateral), but not Group 1 ($r = -.19$, n.s.). The focus on the anticipation function in Group 2 and Group 3 may therefore play a role in the development of more *effective* strategies for those who develop more elaborate ones. Nevertheless, the degree of strategy elaboration is not significantly different across groups, $F(2,27) = .495$, n.s., which could explain the lack of an overall performance benefit for Group 2 and Group 3.

DISCUSSION

The goal of the present experiment was to study the role of two high-level cognitive functions in a complex decision making task: anticipation and strategy development. A noteworthy result was that the overall score of participants in the three conditions was comparable. Focusing on *short-term* consequences, either with or without a decision aid providing correct predictions, was not sufficient to improve the participant's ability to successfully influence the complex system in the *long-term*. This result is particularly counter-intuitive: providing participants with a "crystal ball" that predicted the effects of their decisions for the next game-year did not help them in the long term. Furthermore, short-term anticipation accuracy was not significantly related to performance. This suggests that when dealing with complex systems, long-term planning is critical (see also Gureckis and Love, in press). Nevertheless, we suggest that anticipation accuracy can still provide a useful metric of comprehension of cause-effect relationships in the system and may be very relevant for studies that focus on sensemaking and knowledge acquisition.

An interesting finding was that participants had the impression that the decision aid was helpful, whereas objective measures did not show an overall benefit in terms of goal achievement. This result suggests that subjective assessments of the usefulness of a support tool can be biased and misleading. Finally, we found that the degree of strategy elaboration was positively correlated to goal achievement, but only in Group 2 and Group 3 in which there was an emphasis on anticipation. One possible interpretation of this result is that anticipation (which requires the integration and application of structural knowledge) is a necessary but not sufficient condition for developing effective strategies.

According to Funke (1991), the development of strategic knowledge is mainly a problem of learning to apply structural knowledge. However, it seems that deriving specific actions from structural knowledge in order to achieve one's goals is not straightforward and must be practiced or learned: "Structural knowledge alone is not sufficient to control a large system. Structural knowledge together with proper strategic knowledge is sufficient (probably even necessary) for the control of large systems" (Schoppek, 2002, p.24). Experiments in which structural knowledge was taught have shown mixed results and seem to support this claim (Funke, 1993; Langley & Morecroft, 2004; Putz-Osterloh, 1993; Preussler, 1998; Schoppek, 2002). The present results lend further support to that conclusion. The main outcome of the present work is to contribute to the identification of metrics and support requirements that may guide the development of decision aids for decision making in a complex environment. In light of the present findings, strategy development and long term planning are critical areas that require further research and development in order to help human decision makers deal with complex systems.

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REFERENCES

Allen, J. G., Corpac, P. S., & Frisbie, K. R. (2006). Integrated battle command program: Decision support tools for planning and conducting unified action campaigns in complex contingencies. *Command and Control Research and Technology Symposium,* June 20-22, San Diego, CA.

Burnett, M., Wooding, P., & Prekop, P. (2005). Sense making in the Australian Defence Organisation (ADO) intelligence community. *DSTO-GD-0440 report.* Defence Science and Technology Organisation.

Busemeyer, J. R., & Pleskac, T. J. (2009). Theoretical tools for understanding and aiding dynamic decision making. *Journal of Mathematical Psychology, 53,* 126-138.

DeLaurentis, D., Callaway, R. K. (2004). A system-of-systems perspective for public policy decisions. *Review of Policy Research, 21,* 829-837.

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

Funke, J. (1991). Solving complex problems: Exploration and control of complex systems. In R.J. Sternberg & P.A. Frensch (Eds.), *Complex problem solving: Principles and mechanisms* (pp. 185–222). Hillsdale, NJ: Lawrence Erlbaum Associates Inc.

Funke, J. (1993). Microworlds based on linear equation systems: A new approach to complex problem solving and experimental results. In G. Strube & K.-F. Wender (Eds.), *The cognitive psychology of knowledge* (pp. 313–330). Amsterdam: Elsevier.

Gureckis, T., & Love, B. (in press). Short-term gains, long-term pains: How cues about state aid learning in dynamic environments. *Cognition.*

Halford, G. S., Baker, R., McCredden, J. E., & Bain, J. D. (2005). How many variables can humans process? *Psychological Science, 16,* 70-76.

Horn, B. (2003). Complexity squared: operating in the future battlespace. *Canadian Military Journal, Autumn 2003,* 7-15.

Karakul, M., & Qudrat-Ullah, H. (2008). How to improve dynamic decision-making? Practice and promise. In H. Qudrat-Ullah, J. M. Spector and P. I. Davidsen (Eds.), *Complex decision making: Theory and practice.* Springer Berlin / Heidelberg.

Klein, G., Moon, B., & Hoffman, R. F. (2006). Making sense of sensemaking I: Alternative perspectives. *IEEE Intelligent Systems, 21,* 70-73.

Langley, P. A., & Morecroft, J. D. W. (2004). Performance and learning in a simulation of oil industry dynamics. *European Journal of Operational Research, 155,* 715-732.

Langton, J., & Das, S. (2007). *A framework for building and reasoning with adaptive and interoperable PMESII models.* Air Force Research Laboratory Tehcnical Report AFRL-RI-RS-TR-2007-241.

Lizotte, M., Bernier, F., Mokhtari, M., Boivin, E., DuCharme, M. and Poussart, P. (2008). Image: Simulation for understanding complex situations and increasing Future Force agility. *The 26th Army Science Conference,* Dec. 1-4, Orlando, FL.

Newell, A., & Simon, H.A. (1972). *Human problem solving.* Englewood Cliffs, NJ: Prentice-Hall.

Poulton, E. (1989). *Bias in quantifying judgment.* Hillsdale: Lawrence Erlbaum.

Preussler W. (1998). Strukturwissen als voraussetzung für die steuerung komplexer dynamischer systeme. *Zeitschrift für Experimentelle Psychologie, 45,* 218-240.

Putz-Osterloh, W. (1993). Strategies for know-ledge acquisition and transfer of knowledge in dynamic tasks. In G. Strube, & K. F. Wender (Eds.), *The cognitive psychology of knowledge* (pp. 331-350). Amsterdam: Elsevier.

Schoppek, W. (2002). Examples, rules, and strategies in the control of dynamic systems. *Cognitive Science Quarterly, 2,* 63 - 92.

Sterman, J. D. (2006). Learning from evidence in a complex world. *American Journal of Public Health, 96,* 505-514.

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