Reasoning with Multiple Diagrams: Focusing on the Cognitive Integration Process

Jinwoo Kim and **Jungpil Hahn**
Department of Business Administration
Yonsei University
Seoul, 120-749, Korea
{jinwoo,hahn}@base.yonsei.ac.kr

Abstract

In order to understand diagrammatic reasoning where multiple diagrams are involved, this study proposes a theoretical framework that focuses on the cognitive process of perceptual and conceptual integration. The perceptual integration process involves establishing interdependencies between the relevant data that have been dispersed across multiple diagrams, while the conceptual integration process involves generating and refining hypotheses by combining the individual data inferred from the diagrams. An experiment within the domain of business systems engineering was conducted where verbal protocols were collected. The results of the experimental study reveal that understanding a system represented by multiple diagrams involves a tedious process of visually searching for related information and of conceptually developing hypotheses about the target system. The results also showed that these perceptual and conceptual processes could be facilitated by providing visual cues that indicate where elements in one diagram are related to elements in other diagrams, and contextual information that indicates how the individual datum in one diagram is related to the overall hypothesis about the entire system.

Introduction

A famous Chinese proverb, "A diagram is worth 10,000 words", indicates the powerful impact of diagram use in everyday life (Larkin and Simon, 1987). The usefulness of the diagram for understanding a system has been investigated in various areas, such as qualitative reasoning (Forbus, Nielson & Faltings, 1991), geometric problem solving (Koedinger & Anderson, 1990), economics (Tabachneck & Simon, 1994), medical diagnosis (Rogers, 1996), scientific discovery (Cheng & Simon, 1995), and understanding mechanical systems (Narayanan, Suwa & Motoda, 1995).

However, as the system to be understood becomes increasingly complex, so does the diagram depicting the system, until it becomes practically no longer possible to represent every detail of the complex system within a single diagram. This leads to the need to divide the information presented in the single diagram into multiple diagrams in which closely related entities are segmented and clustered. Each diagram represents a different aspect of the system and plays a different functional role in problem solving (Cheng, 1996). Since a different representation of the system may be needed depending on the nature of the problem, a set of multiple diagrams is designed to support a wide range of problem solving activities. However, only a few studies have dealt with the cognitive processes involved in using multiple diagrams (Cheng, 1996). Even though multiple diagrams are extensively used in common practice, previous research on diagrammatic reasoning have focused on diagrammatic representation within a single diagram. Hence issues concerning the coordination of multiple diagrams or problems concerning the extraction of information from multiple diagrams have not yet been properly addressed (Woods, 1995).

The main objective of this study is to explore the cognitive processes of using multiple diagrams in diagnosing complex systems. This objective is pursued 1) by proposing a theoretical framework and design guidelines for multiple diagrams, and 2) by conducting an experiment that examines the cognitive process of utilizing multiple diagrams in the domain of business system engineering and verifies the usability of the proposed design principles.

Diagrammatic Reasoning as Cognitive Integration of Multiple Diagrams

Diagrammatic Reasoning may be defined as the act of reasoning and problem solving using diagrams as external representations (Narayanan, Suwa & Motoda, 1995). Previous research on diagrammatic reasoning have proposed a cognitive model consisting of two highly interrelated processes; the perceptual process and the conceptual process.

Perceptual and Conceptual Processes

The perceptual process of diagrammatic reasoning is a bottom-up activity of sensing something and knowing its meaning and value (Bolles, 1991). On the other hand, the conceptual process of diagrammatic reasoning is a top-down activity of generating and refining hypotheses (Simon & Lea, 1974) to solve the problem at hand. The powerful impact of the (single) diagram is due to its potential in the perceptual and conceptual processes (Rogers, 1995). In other words, a diagrammatic representation is (sometimes) better than a sentential representation, because the diagrammatic representation helps both the perceptual and conceptual processes in problem solving (Larkin and Simon, 1987). In terms of the perceptual process, the diagrammatic representation, by grouping all relevant information together, helps to identify and recognize relevant items which reduces the amount of search for the elements needed for solving the problem. In terms of the conceptual process, the diagrammatic representation, by providing a large number of perceptual inference cues, helps generate and test hypotheses which is the essence of reasoning (Larkin & Simon, 1987).

Integration Processes with Multiple Diagrams

Multiple diagrams are designed to facilitate human understanding of each constituent diagram, because each individual diagram categorizes closely related entities and organizes them from a single consistent perspective. However, the ease in understanding individual parts of a target system (e.g., one single diagram) does not guarantee the same ease in understanding the entire target system as a whole (e.g., the complete network of diagrams). As the number of diagrams gets larger, the problem solver can only see a small portion of the total system at a time or a very small number of the potentially available displays (Cook et al., 1991). This property is often referred to as the keyhole effect (Woods, 1995). The keyhole effect makes it difficult to understand the entire system because it adds cognitive burdens on 1) remembering where to look next in the entire set of diagrams available behind the currently attended diagram, 2) extracting information across multiple diagrams, and 3) merging the extracted information to build up a coherent representation. Therefore, in order to fully support the use of multiple diagrams, we need to devise a better way to deal with such cognitive burdens caused by the keyhole effect. Yet, the default tendency in designing multiple diagrams is to leave out any cues that indicate in cognitively economical ways whether something interesting may be going on in another one of the multiple diagrams. Instead, the processes involved in overcoming the keyhole effect are forced on the problem solver in a mentally effortful and high memory-load manner (Woods, 1984).

We hypothesize that the perceptual and conceptual processes in the case of the single diagram should also be expanded and applied to the case of multiple diagrams. As we need to efficiently conduct both the perceptual and conceptual processes in order to perform well with a single diagram, we should also be able to perform efficient perceptual and conceptual processes in *integrating* multiple diagrams. In other words, both the perceptual integration and the conceptual integration processes should be conducted well in order to reason properly with multiple diagrams. With multiple diagrams, the *perceptual integration process* consists of linking the relevant visual items that are dispersed across multiple diagrams. In order to perform perceptual integration, we need to locate the diagram to look at next and need to recognize the relevant items in the target diagram. Therefore, in order to facilitate the perceptual integration process, we need to provide visual cues that indicate how a visual item in one diagram is related to other visual items in the other diagrams. The *conceptual integration process* consists of generating and refining hypotheses by linking the information inferred from different diagrams. In order to perform the conceptual integration, we need to discern whether the data provided in the various diagrams are important to the attending hypothesis. Therefore, in order to facilitate the conceptual integration process, we need to provide a broader context that indicates how the individual datum in one diagram is related to the overall hypothesis about the entire system (Woods, 1995). An experiment was conducted to explore the perceptual and conceptual integration processes, and to test the effects of the design principles of multiple diagrams on the integration processes.

Method

Subjects

The subjects were senior undergraduate students at Yonsei University. They participated in the experiment at the end of a semester-long business engineering class, by which time they had completed several homework assignments. None of the subjects had difficulties in understanding the diagrams provided as the experimental material, because the diagrams were of the same kind as practiced in their assignments. The subjects were randomly divided into two groups: control and experimental. Nine subjects were assigned to the control group (CTL), while eight subjects were assigned to the experimental group (EXP). One subject in EXP was discarded from further analysis because of the poor quality of his verbal protocols.

Task Materials

We developed our experimental materials in the domain of business engineering which analyzes an existing business system to diagnose the fundamental source of problems and subsequently designs new business systems (Davenport, 1993). Most business engineering methodologies make use of multiple diagrams from diverse perspectives in order to deal with the inherent complexity of the business system (Taylor, 1995). In order to develop our experimental stimulus, a business system was selected from real-world cases of business engineering projects. The selected system had previously been analyzed by industry gurus and two fundamental problems had been identified (Davenport, 1993).

Two sets of diagrams were constructed for the selected system. The first set of diagrams, which were given to CTL, were drawn according to the existing major methodology (Rumbaugh et al, 1991). Eleven diagrams were drawn in total. Two modifications were made to the first set of diagrams in order to draw the second set of diagrams that were given to EXP. One modification was made to provide visual cues that would help search related items across different diagrams. This was done by restructuring one class of diagrams so as to make it visually similar to another class of diagrams (Edelman, Cutzu & Duvdevani-Bar, 1996). The original diagram whose purpose was to show the flow of messages between objects represented objects as vertical lines and messages exchanged between the objects as arrows between the vertical lines. These diagrams were restructured to a node-arc structure (objects as nodes and messages as arcs) which was visually similar to the diagram that depicted the static structure of the system. The visual similarity was expected to help easily relate these diagrams. The second modification was made to provide a broader context through which the problem solver would identify the relative importance of individual items with regard to the attending hypotheses. This was achieved by providing a diagram that represented the overall dynamics of the system. In the original set of diagrams each business process was represented in its respective diagram. The modification merely grouped all the business processes into a single diagram thus showing all the processes of the entire business system at a high level of abstraction. The high level grouping was expected to help the problem solver reflect on the individual information inferred from the other diagrams with an overall view of the entire system. As a result of the two modifications, the second set of diagrams consisted of a total of fourteen diagrams.

Even though the number of diagrams differed between the two groups, the two sets of diagrams were drawn so that they were informationally equivalent (Larkin and Simon, 1987). In order to verify the information equivalence, the two sets of multiple diagrams were translated back to natural language descriptions. Then, the two translated natural language descriptions were compared and the diagrams were revised to resolve the discrepancies between the two. These steps were iterated several times to make sure that the two sets of diagrams provided an equivalent amount of information.

Experimental Procedure

The experimental sessions were divided into four sections. First, the subjects were given instructions about the general nature of the experiment and were told that verbal protocols would be collected. Subjects were trained to "think-aloud" using two traditional tasks (Ericsson and Simon, 1993). The subjects were then given the task of diagnosing the business system based on the given diagrams. The subjects were given ninety minutes to understand the given diagrams and come up with what they thought were the fundamental problems in the business system.

Data Analysis

Protocol analysis (Ericsson & Simon, 1993) was used to investigate the cognitive processes involved in using multiple diagrams. The data concerning the perceptual integration process were coded based on the action protocols. The perceptual data were about the particular diagram the subjects were paying attention to during problem solving. The subject's perceptual activity was coded as paying attention to a certain diagram if he/she identified the title of the diagram or if he/she located a certain visual item in the current diagram. The activity of deliberately switching between two diagrams in order to identify the relationships between them was also coded as perceptual data. Each subject's perceptual data were summarized into a Diagram Transition Graph (DTG) that depicts the trajectory of the subject's transitions among the multiple diagrams during the entire problem solving session.

The data concerning the conceptual integration process were coded based on the subjects' concurrent verbal protocols. The conceptual data consisted of the hypotheses about the potential problems in the given business system. Any verbal utterance that contained the subject's opinion about the business system was coded as a hypothesis. For example, a subject could directly come up with a problem (*"It takes four hours to prepare for the meals everyday. That's too much."*), or ponder upon the basic rationale about the current process (*"why does she have to input the order in such a way?"*), or infer consequences not given in the diagrams (*"she must be pretty tired after taking care of all that stuff"*). The subject could also refine or nullify a hypothesis he/she had made earlier. The conceptual data were summarized into a Hypothesis Behavior Graph (HBG) which is similar to the Problem Behavior Graph proposed by Newell and Simon (1972) and which indicates how subjects generated new hypotheses and later refined or nullified them. Examples of the DTG and HBG are shown in the following section.

Results

Overall Performance

The overall performance was measured by counting the number of correct problems the subjects had identified during the diagnostic process. In CTL, only two subjects were able to identify all of the two correct problems, three subjects identified only one of the two problems and four subjects could not come up with any problem at all. In EXP, six subjects came up with the two correct problems while one subject came up with a single problem. These results suggest that the overall performance of EXP was improved compared to the performance of CTL (Chi-square=6.86, $p<0.05$).

Detailed protocol analyses of the subjects in each group were conducted to identify the possible differences in cognitive processes undergone, which would account for the difference in performance. Although comprehensive analysis of the verbal and action protocols most accurately shows the dynamic nature of cognitive integration, it is impossible to present all the data in detail for all the subjects because of the space limit. Therefore, for each group, we decided to present the analysis of one subject in detail and then compare the aggregate protocol results between the two groups. The subject to be analyzed in detail for each group was selected because his/her cognitive processes were relatively simple and representative of the behavior of the group.

Detailed Individual Process Data

The Perceptual Integration Process. The perceptual process was analyzed based on the subject's DTG. Figures 1 and 2 show the DTGs of the representative CTL and EXP subjects, respectively. The DTG indicates how the subjects' attention shifted during the experiment by showing the sequence of transitions among the diagrams. The vertical axis represents the different diagrams provided to the subject, while the horizontal axis represents the passage of time.

Comparison of the two figures indicates that the perceptual behavior of the two subjects are radically different in two aspects: the number of diagram transitions and number of round-trips. First, the lines between two dots in the figures stand for diagram transitions. We can see that the EXP subject went through many more diagram transitions than the CTL subject (68 for CTL; 438 for EXP). The difference is significant considering the same time limit assigned to both groups. Second, the ∧ and ∨ shapes in the figures stand for round-trips where the subjects refer to another diagram and return to the initial diagram of interest. The figures show that the EXP subject made many more round-trips than the CTL subject (13 For CTL; 204 for EXP).

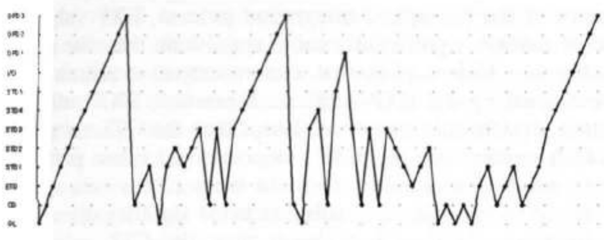

Figure 1: DTG of a representative CTL subject

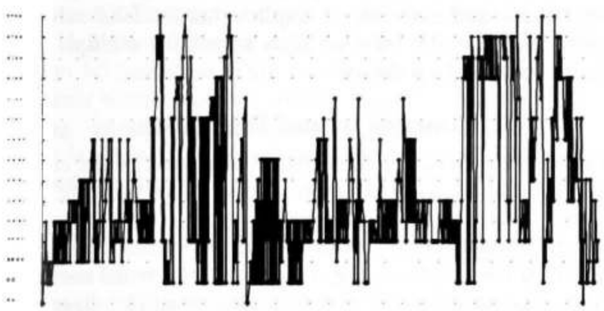

Figure 2: DTG of a representative EXP subject

The above analyses point to several interesting facts as to the nature of the perceptual integration process with multiple diagrams. The larger number of diagram transitions by the EXP subject implies that he could perform a more extensive search than the CTL subject. Moreover, the larger number of round-trips by the EXP subject implies that his search is not just a random walk, but a purposeful endeavor to relate pairs of related diagrams. This may be possible because visual cues in the diagram given to the EXP subject allowed him to easily locate the related diagrams among the available diagrams.

The Conceptual Integration Process. The conceptual process was analyzed based on the subjects' HBGs that represent the hypotheses generated by a subject in order of occurrence. Figures 3 and 4 show the HBGs of the representative CTL and EXP subjects, respectively. Each rectangle represents a hypothesis generated by the subject. Refinement of a previously generated hypothesis is denoted as one placed one step to the right, whereas an entirely new hypothesis is placed on a different row one step below. The hypothesis number and the number of refinements for the particular hypothesis is denoted on the right side of the square. The temporal sequence of occurrence of the hypotheses is represented by its spatial location on the horizontal axis, from left (early) to right (late). The diagrams involved in the generation (and refinement) of the hypotheses are represented by the diagram name under each square. For example, the Hypothesis Behavior Graph in Figure 3 shows that the subject generated her first hypothesis (H1-1) while attending to the Class Diagram (CD).

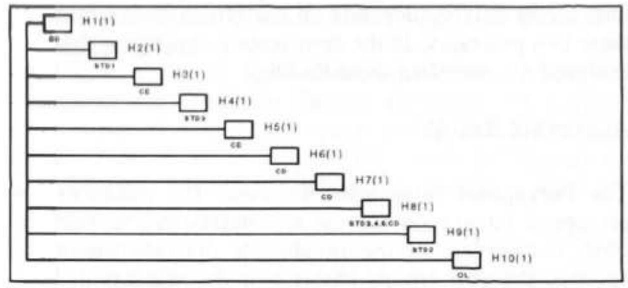

Figure 3: HBG of a representative CTL subject

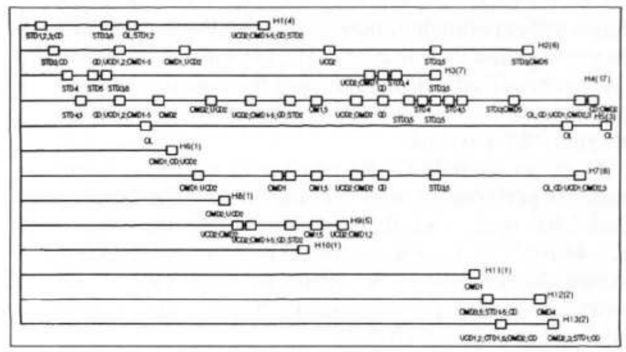

Figure 4: HBG of a representative EXP subject

We can see from the figures that the conceptual behavior of two subjects were radically different in two aspects: the number of hypothesis refinements and the number of different diagrams involved in developing the hypotheses. First, even though the number of hypotheses generated are similar to each other (10 for CTL; 13 for EXP), the EXP subject refined the generated hypotheses much more often than the CTL subject. In fact, the CTL subject never refined hypotheses that had been generated earlier, while the EXP subject made 58 refinements in total, more than 4 refinements per hypothesis on average. Second, we can see from the figures that the CTL subject mostly referred to only one diagram per hypothesis (except for her eighth hypothesis where four diagrams were involved), while for the EXP subject the refinement of a previously generated hypothesis was triggered by the examination of different diagrams from the one originally used in the initial generation.

Since information about a certain entity is dispersed over multiple diagrams following the perspective of each diagram, the refinement process of the hypotheses should consist of integrating multiple perspectives of the system into a single, composite representation. Therefore, different diagrams came into play in the hypothesis refinement process of the EXP subjects. The contextual cues built into the diagrams given to the EXP subject are assumed to have allowed him to evaluate the various data dispersed over the multiple diagrams from a consistent perspective of attending hypotheses.

In summary, the findings of the detailed analyses suggest that problem solving with multiple diagrams involves two closely related cognitive processes : a perceptual integration process and a conceptual integration process. Success in problem solving depends on the effective execution of these two processes. In the next section, aggregate data are analyzed to generalize these findings.

Aggregate Results

The Perceptual Integration Process. The results of the perceptual integration process are summarized in Table 1. First, comparison of the number of diagram transitions between the two groups shows that the subjects in EXP performed more diagram transitions than those in CTL (98.89 for CTL vs. 345.71 for EXP; $t(14)=6.538$, $p<0.001$). Since the experimental material for EXP consisted of three more diagrams than that of CTL, the number of transitions were normalized per diagram and the results remained significant (8.24 for CTL vs. 23.05 for EXP group; $t(14)=5.783$, $p<0.001$).

Next, we examined the number of episodes where the subjects performed round-trip transitions. The results show that EXP made significantly more round-trips than CTL (26.44 for CTL vs. 136.14 for EXP; $t(14)=5.327$, $p<0.001$). Again, the difference was significant even when the results were normalized per diagram (2.20 for CTL vs. 9.08 for EXP; $t(14)=4.928$, $p<0.001$).

	Total Transitions	Returning Episodes
CTL	98.89	26.44
EXP	345.71	136.14

Table 1: Perceptual Integration Process

The Conceptual Integration Process. The results of the conceptual integration process are summarized in Table 2. First we examined the number of hypothesis refinements. The EXP subjects developed an average of 10 hypotheses and these hypotheses were refined an average of 40.57 times, giving an average of 4.057 refinements per hypothesis. On the other hand, the CTL subjects produced an average of 6.78 hypotheses and these hypotheses were refined an average of 10.67 times, yielding an average of 1.574 refinements per hypothesis. Thus, the EXP subjects showed significantly more refinements than the CTL subjects ($t(14) = 4.450$, $p < 0.001$).

	# of Hypotheses	# of Refinements	Ref / Hyp	Diagrams / Hyp
CTL	6.78	10.67	1.574	1.787
EXP	10.00	40.57	4.057	4.671

Table 2: Conceptual Integration Process

Next, we examined the diagrams used in the hypothesis-development process. Table 2 also shows the number of diagrams used in the process. An average of 4.671 diagrams were involved in developing each hypothesis by the EXP subjects, while the CTL subjects used less than two (1.787) diagrams per hypothesis. Therefore, the EXP subjects showed a more intensive usage of the diagrams for generating and refining hypotheses about the target system ($t(14) = 6.343$, $p < 0.0001$).

In summary, the aggregate results show similar patterns of the cognitive integration behaviors as those observed in the detailed process data of the representative subjects. In terms of the perceptual integration process, EXP subjects went through significantly more transitions than the CTL subjects, which implies that a more extensive search was performed by the EXP subjects. Moreover, EXP subjects made significantly more round-trips than the CTL subjects, which implies that the EXP subjects could relate pairs of relevant diagrams more easily. In terms of the conceptual integration process, EXP subjects made significantly more refinements to their hypotheses than the CTL subjects. Moreover, EXP subjects employed more diagrams in refining their hypotheses, which implies that the EXP subjects could integrate the relevant data across the multiple diagrams for their hypotheses.

Conclusion and Discussion

This paper provides a theoretical framework of the cognitive processes involved in reasoning with multiple diagrams. The cognitive integration process comprises the perceptual and conceptual integration processes. This paper also identifies useful design factors such as visual cues and contextual information for designing multiple diagrams, and applies them to the design of diagrams in business engineering. The results from the experimental study indicate that the visual cues provided as in the diagrams facilitated the perceptual integration process resulting in more transitions between the multiple diagrams and especially, more transitions between pairs of two related diagrams in search of further information. The contextual information also turned out to facilitate the conceptual integration process resulting in a more thorough refinement on the generated hypotheses and in a more versatile use of diverse diagrams in the hypothesis refinement process.

The theoretical contribution of this paper is in its proposal of a framework for the cognitive integration process in reasoning with multiple diagrams. This paper proposed two dimensions of cognitive integration (i.e., the perceptual and conceptual integration process), analytical methods to investigate the dynamic process of the integration (i.e., the data transition graph and hypothesis behavior graph), and prescriptive ways to facilitate the integration process in the two dimensions (i.e., visual cues and contextual information).

The practical contribution of this paper stems from the prevalence of multiple diagrams in business systems engineering because when modeling complex systems the usage of multiple diagrams is the norm rather than an exception. At the same time, the current trends in business systems engineering place more emphasis on the design diagrams rather than on the final programming codes (Winograd, 1995). However, more diagrams do not directly increase the analysts' understanding of the target system unless the diagrams contain enough visual cues and contextual information to assist the reasoning activity. Thus, the increased role of diagrams in design documentation is expected to add more significance to the results of this paper.

However, this study has limitations which need to be investigated in future research. First, we need to identify the general features of the diagrammatic representation that are most appropriate for the reasoning task and explore their impact on diagrammatic reasoning. For example, what kinds of visual cues and contextual information are more appropriate for allowing people to relate the visual features in the multiple diagrams or to compare various conceptual hypotheses about the system. Second, features concerning the reasoning task itself need to be investigated. In this study the reasoning task was focused on integrating information dispersed around multiple diagrams. However, the reasoning task may be extended to a broader range of diagram use. In addition to integrating multiple diagrams, dividing a diagram into several partitions or omitting elements from a diagram in order to obtain a diagram that is easier to understand are diagrammatic reasoning tasks that need to be examined. This would call for an *Algebra of Diagrams* where problem solving consists of adding, subtracting, multiplying and dividing diagrams. Future research is directed at identifying the key features in performing these tasks.

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