Effects of Knowledge Representation on Knowledge Acquisition and Problem Solving

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Abstract: The way knowledge is represented influences the effectiveness with which that knowledge can be shared and reconstructed. Of particular interest to this study is the hypertext knowledge representation. Based on the schema theory, we propose a model explaining the effect of the hypertext knowledge representation on the user's problem solving performance. The sophistication of the knowledge structure that the user can construct from the hypertext knowledge representation is proposed as an intervening variable mediating the effect of hypertext on the problem solving performance. According to our model, the hypertext representation of the "collective schemata" of a group of experts allows the user to acquire a more complex and better integrated knowledge structure that is more similar to the experts' than does a linear representation. The model further hypothesizes that the complexity, integration and degree of similarity of an individual's schemata to that of domain experts in turn improves significantly the individual's problem solving performance. Compared to the linear representation, the hypertext representation of expert knowledge is expected to improve the quality of problem solving in the organization through the facilitation of the acquisition of more sophisticated knowledge structures by the users. A field experiment was used to verify the hypotheses of our model. This research demonstrates the important role of hypertext knowledge representation in supporting knowledge construction and problem solving.

Keywords: Hypertext, knowledge representation, knowledge elicitation, knowledge construction, problem solving

1. Introduction

The way knowledge is represented influences the effectiveness with which that knowledge can be shared and reconstructed. Traditionally, knowledge is presented in a linear way, following a hierarchical structure. Learners have no control over the sequence of learning materials and the association among concepts is not explicit. With hypertext, on the other hand, knowledge can be represented as a network of linked nodes. The nodes can include a variety of knowledge representations such as free text, structured data, mathematical and other types of models as well as multimedia representations. The links can portray semantically significant relationships varying from cause-effects to logical and mathematical associations. Hypertext, as a knowledge representation scheme and also as a user interface modality, has been indicated to support mental model building and mental model maintenance by enabling scanning and focused search (Vandenbosch and Higgins 1996). Another important feature of hypertext is that it allows for different levels of prior knowledge (Stanton and Stammers, 1990). With linear text, the learner may have to go through already known material sequentially before reaching new information. This could have negative effects on the learner's motivation. With hypertext, on the other hand, the learners are more active in selecting the material to explore and have more browsing flexibility. Also important to mention is the ability of hypertext to provide contextualized access to domain knowledge. This hypertext feature has been shown to enhance understanding, to reduce the motivational 'cost' of learning and to be highly effective for resolving comprehension difficulties (Mao and Benbasat, 1998).

In this study, we compare the hypertext representation of expert knowledge to the traditional linear text representation in terms of the effects on the transfer and reconstruction of complex knowledge structures. Based on the schema theory, we propose a model explaining the effect of the hypertext knowledge representation on the user's problem solving performance. The sophistication of the knowledge structure that the user can construct from the hypertext knowledge representation is proposed as an intervening variable mediating the effect of hypertext on problem solving performance. According to our model, the hypertext representation of the "collective schemata" of a group of experts allows the user to acquire a more complex and better integrated knowledge structure that is more similar to the experts' than does a linear representation. The model further stipulates that the complexity, integration and degree of similarity of an individual's schemata to that of domain experts in turn improves significantly the individual's problem solving performance. Compared to the linear representation, the hypertext representation of expert knowledge is expected to improve the quality of problem solving in the organization through the facilitation of the acquisition of more sophisticated knowledge structures.

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The paper is structured as follows. We first describe the research model and justify its hypotheses. This is followed by a description of the empirical study and a discussion of the results. In conclusion, we summarize the study, discuss the theoretical and practical implications and make suggestions for future research.

2. Research model

Our model (see Figure 1) stipulates that knowledge representation determines knowledge acquisition, which in turn affects problem solving performance. As far as knowledge acquisition is concerned, an important advantage of hypertext is its non-linearity and more particularly its capability of representing associative relationships. According to the schema theory (Rumelhart, 1984), knowledge is stored in long-term memory as a network of information packets: schemata. These schemata are abstract, structured and dynamic. They are viewed as semantic networks or meaningfully related concepts (Jonassen and Reeves 1996). These networks are dynamic in the sense that they are continuously reconstructed through knowledge acquisition. The schema theory defines knowledge acquisition as the process of interpretation of new information and its assimilation and accommodation into schemata (Anderson and Pearson, 1984). Assimilation is the incorporation of new information into an already existing schema and accommodation refers to the modification of an existing schema to fit in new information. After several reorganizations of his/her knowledge structure, the novice forms a schema that resembles that of an expert (Shavelson 1974).

Hypothesis 1: The hypertext representation of expert knowledge will enable the user to acquire a significantly more sophisticated knowledge structure than with the linear representation of the same knowledge.

The sophistication of a knowledge structure is defined in terms of its complexity, its level of integration (interconnectedness) and its structural closeness to the experts' knowledge. Complexity and integration are the main characteristics that differentiate the knowledge structure of the expert from that of the novice. More able individuals have richer, more interconnected knowledge structures than do less able individuals (Derry 1990). As expertise is attained through learning, the elements of knowledge become increasingly interconnected (Ruiz-Primo and Shavelson 1996). In addition to growing more complex and better integrated, the semantic networks of novices also become more structurally similar to those of an expert with learning (Royer et al. 1993). It is not just the number of elements of knowledge (complexity) and the number of connections between these elements (integration) that matter, but also which particular connections are made (structure).

Hypothesis 2: The level of sophistication of an individual's domain knowledge structure affects positively the individual's problem solving performance in that domain.

Knowledge structure represents an important dimension of the acquisition of cognitive skills (Mandin et al. 1997). A number of studies established a significant relationship between the knowledge structure and problem solving performance (e.g., Robertson 1990; Markham et al. 1994). The similarity of an individual's domain-specific knowledge structure to that of an expert correlates significantly with measures of achievement (Markham et al. 1994). In our model, problem-solving performance is measured in terms of performance time, the appropriateness of the solution (as judged by domain experts) and the individual's rationale or justification of the solution (also as evaluated by domain experts). As our model explains the effect of hypertext on the acquisition of explicit knowledge as opposed to tacit knowledge, the ability of the user to justify the solution is an important aspect of the user's performance.

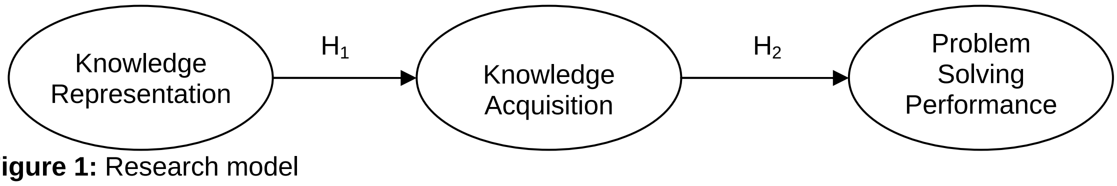

Figure 1: Research model

3. Empirical study

To verify the hypotheses of our model, we conducted a between-subjects field experiment involving eighty business professionals enrolled as part-time MBA students. Participation was voluntary and remunerated. The subjects were randomly assigned to two groups: a control group and an experimental group. The control group used a computer-based linear representation. The experimental group, on the other hand, had access to a hypertext representation of the same material. The two groups were compared in terms of knowledge acquisition (i.e., sophistication of knowledge structure) and knowledge application (i.e., problem-solving performance).

3.1 Experimental procedure

We conducted a knowledge elicitation process with a group of bank loan officers (domain experts) regarding the evaluation of personal loan applications. The process resulted in a collective concept map describing the loan applications evaluation that all participants agreed upon. We then used the resulting experts' concept map to design the navigational structure of a hypertext system, where each node was presented with a separate screen describing the associated concept(s) and links (cross-links). Such associated information was highlighted with hyperlinks, allowing for the access to the neighborhood (related concepts) of the node. We also developed a linear computer system including the same screens as the hypertext system, but without the hyperlinks. The two systems had the same look and feel. The only difference was in the navigational structure.

The experiment involved three stages performed on three different days. In the first stage, the subjects received a briefing on the experimental procedure and then attended a tutorial on concept mapping. A test revealed no group difference in terms of map complexity and integration. In the second stage of the experiment, the subjects participated in a knowledge acquisition session followed by a concept mapping session. The experimental group used the hypertext system while the control group used the linear system to learn about the evaluation of loan applications. The knowledge acquisition session lasted 45 minutes. After a recess of 15 minutes, the subjects were given 30 minutes to draw a concept map describing the loan application evaluation process. The duration of both sessions was determined by a pilot experiment. To motivate the subjects to perform at the best of their ability, they were informed since the first stage of the experiment that the best concept map would be selected for a monetary prize ($200).

In the third stage of the experiment, the subjects were given three loan applications to evaluate. No time limit was imposed, but the subjects were told to perform the evaluation as fast as possible and that the fastest correct evaluation would receive a monetary prize (another $200). The first loan application was a straightforward case, satisfying both objective criteria (eligibility ratios) and subjective factors (risk and character). The second application satisfied the objective criteria but failed some important subjective criteria. More specifically, the loan officers judged the application risky because of lack of residency stability and insufficient assets. The third application did not satisfy the objective criteria because of the lack of the credit bureau rating, as the applicant did not have any credit history. It was, however, accepted by the loan officers because it scored high on the subjective criteria. The risk and character factors were judged as good and the applicant had sufficient assets to cover the loan. After the subjects evaluated all three cases, they were interviewed individually and asked to justify their evaluations. The interviews were audio-taped and later analyzed by loan officers.

3.2 Measurement

Knowledge structure acquired by the subjects in a specific domain was assessed with concept mapping (second stage of experiment). The sophistication of a subject's knowledge structure was determined by the complexity and integration of the subject's concept map and the closeness of the map to the referent knowledge structure (the experts' concept map). The total number of valid direct links measured complexity, while the total number of valid cross-links measured integration. Three loan officers that were not involved in the knowledge elicitation phase determined the validity of the nodes, links and cross-links. The three loan officers performed the validity judgment separately. In case of disagreement about the validity of a node or a proposition, they were asked to reevaluate the entire map without being informed of each other's evaluation. If after the second round the disagreement was not resolved, the opinion of the majority (two out of three) was selected. The closeness of a subject's map to the experts' map was measured with the *C metric* (Goldsmith and Davenport 1990). The C metric measures the degree of similarity of the neighborhood of a given node, in the subject's map, to the neighborhood of the same node in the referent map. The C metric is determined for every node in the subject's map. Cs for individual nodes were then averaged across all nodes in the map to produce a single C value that indicates the overall similarity of the subject's map to the experts' map.

Three different measures of problem solving performance were considered: 1) total time spent on the evaluation of the three loan applications in phase 3 of the experiment, 2) the appropriateness of the solution (evaluation) and 3) the justification of the solution. Solution appropriateness refers to the ratio of agreement of the subject's evaluations with the loan officers' evaluations of the three cases (1/3 for one match, 2/3 for 2 matches and 1 for complete agreement). Solution justification was rated by the three loan officers who validated the subjects' concept maps, based on the audiotaped interviews. The rating was done according to the Structure of the Observed Learning Outcome (SOLO) taxonomy (Biggs and Collis 1982). Higher levels in the SOLO taxonomy correspond to higher levels of understanding of the problem domain. The SOLO scores given by the three loan officers were averaged to produce a unique score for each subject, after verification of inter-rater reliability.

4. Results and Discussion

As indicated in Table 1, the experimental group achieved significantly higher scores for knowledge structure complexity, integration and closeness. These results provide strong support for hypothesis 1. The experimental group also attained significantly better performance: faster in problem solving, higher agreement ratios with experts and higher SOLO scores for solution justification, providing strong support for hypothesis 2. These results are consistent with previous studies that reported positive effects of semantic networks on achievement measures (e.g., Khalifa and Limayem 1994; Khalifa and Lam 2002).

Table 1: Comparison of means

	Means for Control group	**Means for exp. group**	**Sig. (p)**
Structural Knowledge Sophistication			
- Complexity (number of direct links)	15.12	19.75	.000
- Integration (number of cross-links)	2.00	4.65	.000
- Closeness to referent structure (C metric)	0.32	0.53	.000
Problem Solving Performance			
- Performance time (in minutes)	43.52	33.37	.000
- Solution appropriateness (agreement ratio)	0.40	0.75	.000
- Solution justification (SOLO score)	2.90	4.17	.000

The measurement of knowledge structure sophistication and problem solving performance was examined with factor analysis, resulting two factors as indicated in Table 2. All indicators had high and significant loadings with respective constructs, demonstrating the construct validity and the discriminant validity. The reliability and convergent validity of the measurement model of this construct were confirmed by the composite reliability of the scale and the average variance extracted (Fornell and Larcker 1981), which all exceeded the recommended value of 0.8 (Nunnally 1978).

Table 2: Factor Analysis Results

	Knowledge Structure Sophistication	**Problem Solving Performance**
Complexity	0.86	
Integration	0.81	
Closeness	0.92	
Performance time*		0.89
Solution appropriateness		0.90
Solution justification		0.82
* Reversed item.		

To test the mediation effect, we computed the factor scores for both knowledge structure sophistication and problem solving performance. The regression analysis (OLS) was conducted and the results support the hypothesized mediating role of knowledge structure sophistication, as illustrated in Table 3: 1) knowledge representation significantly affects the mediator (0.853^{**}); (2) knowledge representation significantly affects problem solving performance in the absence of the mediator (0.726^{**}), (3) the mediator has a significant unique effect on problem solving performance (0.64^{**}), and (4) the effect of knowledge representation on problem solving performance shrinks upon the addition of the mediator to the model ($0.726^{**} \rightarrow 0.181$). We also performed a formal test (Sobel-Test) as recommended by Baron and Kenny (1986) and a significant z-value of 4.63 ($p<0.01$) was observed. These results provide a strong indication that a significant part of the relationship between knowledge representation and problem solving performance can be explained by the effect of knowledge representation on the sophistication of the knowledge structure acquired by the user. In this particular case, the hypertext knowledge representation seems to lead to a faster, more appropriate and better justified problem solving performance mainly because it supports the construction of a more complex, better integrated and more expert-like knowledge structure than the linear representation. Although other hypertext features may still affect problem solving positively, it is the capability of hypertext to mimic the associative nature of human memory that seems to be the most important. This particular feature is the basis for the hypothesized effect of hypertext knowledge representation on knowledge structure sophistication, which is shown to be mediating a significant part of the effect of hypertext on problem solving.

Table 3: Regression Results for Mediation Test

	Coefficient
Reduced Model: R^2=0.527	
Knowledge Presentation → Problem Solving Performance	0.726**
Full Model: R^2=0.639 R^2=0.727 (KSS)	
Knowledge Presentation → Problem Solving Performance	0.181
Knowledge Presentation → Knowledge Structural Sophistication (KSS)	0.853**
Knowledge Structural Sophistication → Problem Solving Performance	0.64**

5. Conclusion

This research demonstrates the important role that hypertext knowledge representation can play in supporting knowledge acquisition and problem solving. The hypertext representation of expert knowledge is shown to help the users to reconstruct and apply that knowledge. More importantly, a model explaining the superiority of hypertext over linear knowledge representation is developed and empirically tested. According to this model, the hypertext knowledge representation assists the user in the acquisition of a more sophisticated knowledge structure that enhances the user's application of the acquired knowledge to problem solving. The level of sophistication of the knowledge structure constructed by the user is shown to mediate the effects of hypertext on problem solving. The results of this study have several implications. Firstly, the explicit representation of a referent knowledge structure in the hypertext navigational structure is an effective method for facilitating the acquisition of a similar knowledge structure by the user. Designed in this was, hypertext can play an important role in constructivist learning environments, where the learners are encouraged to actively create knowledge through free exploration of learning material. Hypertext can then be used to help the learner acquire an initial knowledge structure that serves as a framework for the interpretation of new information. This initial knowledge structure can be developed further through other learning method such as collaborative learning. Secondly, when the referent knowledge structure embedded in the hypertext navigational structure is that of an expert or a group of experts, hypertext-based systems, e.g., corporate Intranets, help other employees to acquire this knowledge and apply it effectively to problem solving. In such a case, hypertext can be considered as a valuable tool for supporting organizational memory. Thirdly, the usage of concept mapping for the elicitation of expert knowledge and for the design of the hypertext navigational structure is proven to be effective. Concept maps have been used for a long time in educational psychology research to measure change in the learner's knowledge structure. They can also be applied to the design of effective hypertext. Now that hypertext is becoming widely used with the proliferation of Internet and Intranet applications, the development of more effective methodologies and tools for the design of such systems is more needed than ever. In the knowledge elicitation stage of our empirical study, we used a collaborative concept mapping approach to derive the collective knowledge structure of a group of expert. Such an approach enabled us to develop an explicit representation of what used to be mainly informal knowledge. The associative structure of concept maps, make them also suitable for mapping the elicited knowledge directly onto the hypertext navigational structure. The potential of concept mapping as a hypertext design tool should be investigated further in future research.

Also in future research, the integration of hypertext with collaborative technologies should be investigated. While the hypertext knowledge representation can play an important role in the explicit representation of a referent expert knowledge structure, collaborative technologies can assist in the communication and further development of this structure. Lim et al. (1997) have shown that a co-discovery approach to learning leads to the acquisition of a mental model with higher inference potential than a self-discovery approach. Furthermore, with collaborative hypertext, knowledge representation and knowledge sharing can be integrated. Starting with a referent expert concept map, the users can discuss the embedded knowledge structure and build upon it. Such an approach has the potential of improving the effectiveness/efficiency of the knowledge construction process and leaves more room for creativity (i.e., developing novel knowledge structures) than using hypertext alone.

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