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Supporting Problem-Solving Performance Through the Construction of Knowledge Maps

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The purpose of this article is to provide five empirically-derived guidelines for knowledge map construction tools that facilitate problem solving. First, the *combinational representation principle* proposes that conceptual and corresponding procedural knowledge should be represented together (rather than separately) within the knowledge map. Second, the *contextual enhancement principle* proposes that the learner should provide information regarding the context of the problem within the knowledge map. Third, the *spatial flexibility principle* proposes that the space where learners represent concepts should be flexible and not artificially constrained. Fourth, the *property association principle* proposes that the magnitude of association between concept and associated processes should be classified by the learner within the knowledge map. Fifth, the *multiple representation principle* proposes that the knowledge map construction tool should have the capacity to represent concepts through multiple modalities. The article presents a prototype of a new knowledge map construction tool that incorporates each of these principles.

Using external representations through symbols and objects to illustrate a learner's knowledge and the structure of that knowledge can facilitate complex cognitive processing during problem-solving (Vekiri, 2002; Zhang, 1997). Such external representations can help a learner elaborate the problem statement, transform its ambiguous status to an explicit condition, constrain unnecessary cognitive work, and create possible solutions (Kosslyn, 1989; Scaife, & Rogers, 1996). Larkin (1989) argued that an external representation supports human problem-solving by reducing the complexity of a problem and its associated mental workload. Moreover, Bauer and Johnson-Laird (1993) showed that diagrams helped learners solve a problem more effectively and efficiently.

Potential instructional uses of external knowledge representations include the following: (a) clarification or elaboration of a learner's own conceptual understanding of a problem space (Stoyanov, 1997); (b) communication of a learner's conceptual understanding to others (Okebukola, 1992); and, (c) evaluation of a learner's conceptual understanding. The focus here is the first use: that is, the learners' use of external representations to aid in their interpretation and understanding of concepts and procedures, as a way to facilitate problem-solving. The purpose of this article is to provide empirically-derived guidelines for designing such external representations (i.e., knowledge maps) to facilitate performance in solving complex problems. Later, a prototype of a computer-based tool that incorporates these principles is presented.

KNOWLEDGE REPRESENTATIONS AND LEARNING

There are numerous forms of representation that facilitate learners in externalizing their internal knowledge structure during problem-solving. Examples include the following ((Kosslyn, 1989; Vekiri, 2002):

1. *graphs* that compare the relations among variables;
2. *charts* that illustrate the flow of discrete events;
3. *maps* that arrange symbolic objects spatially; and
4. *diagrams* that show relationships through objects and lines.

Of these external representations, knowledge maps that connect concepts (i.e., "nodes") through labeled (or sometimes unlabeled) arrows (i.e., "links") have been found to be particularly very highly effective for problem-solving (Jonassen, Beissner, & Yacci, 1993).

The theoretical rationale for knowledge mapping is based in part on Ausubel's assimilation theory (Ausubel, 1968), which suggested that learners think about concepts as well as the relations among them when they process information. The learner links new concepts to more generalized concepts that are already stored in his or her internal cognitive structures. Another theory underlying the knowledge map is semantic networking theory (Collins & Loftus, 1975), which hypothesizes that human memory is organized semantically. These existing networks of concepts, referred to as "schemas," are linked with new knowledge when learners form new connections to them.

Specifically, the knowledge map is an externalized graphical representation that describes the relations among nodes by use of bi-directional links that define properties among the nodes (Fisher, 2000a). For example, an arrow labeled "has," from the node labeled "Mary" to the node labeled "pencils" represents the sentence "Mary has pencils." Figure 1 is the graphical

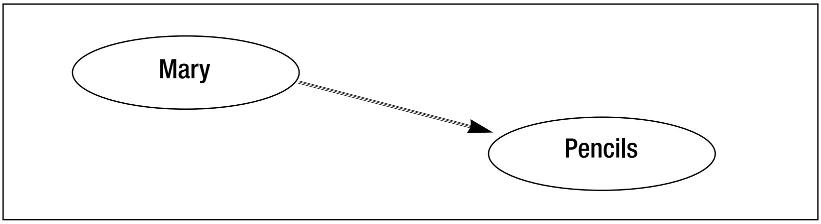

Figure 1. An example of a knowledge map

representation of this sentence.

Depending on researchers' preferences or computer software conventions, such maps are sometimes referred to as "cluster maps," "mind maps," "concept circle diagrams," "concept maps," "semantic networks," or "conceptual graphs" (Fisher, 2000a). The links of cluster maps and mind maps, for example, are unlabeled whereas concept maps, semantic networks, and the links of conceptual graphs are labeled. Moreover, different types of maps serve different educational purposes. For instance, concept circle diagrams illustrate larger categories into which smaller concepts are grouped. Irrespective of their names, these forms have the common characteristics that they assign and link important concepts with labeled or unlabelled lines.

There are several ways in which knowledge maps can support learning in general. First, learners can construct knowledge maps for representing their understanding in a domain. By creating a knowledge map during the learning process, they can reconceptualize, elaborate, and refine concepts that they already know. Second, this process can facilitate their recognition of patterns and relationships among the concepts as a way to promote meaningful learning. Third, knowledge map construction facilitates learner reflection by requiring that they consider what they know and do not know as they attempt to construct meaningful knowledge in terms of nodes and links, which is frequently a difficult process. Fourth, knowledge maps can be used as instructional material where a teacher presents learners with concepts, and relationships among them, in a new content domain. Finally, knowledge maps can be used as a external measure (or indicator) of the learner's internal knowledge structure in memory. Along this line, the teacher can assess learners' progressive development by comparing their knowledge maps to those of experts or by assessing the knowledge maps according to specific evaluation criteria, such as the number of nodes and links (Novak & Musonda, 1991).

The knowledge map is especially useful for facilitating problem solving. Knowledge maps can enable learners to do the following: (a) externalize their internal problem-solving processes and thus recognize useful information embedded in the problem; (b) retrieve and reorganize their prior knowledge with new knowledge that is selectively related to the problem; (c) identify possible constraints; and, (d) generate insightful ideas (Hayes, 1989; Sherman & Grueneberg, 2000; Stoyanov, 1997). For example, Osmasta and Lunetta (1988) tested the effect of a concept linkage technique on problem-solving performance in physics with two different physics problems (local and global). They found that physics teachers who interrelated the local and global problems with concept mapping enhanced student conceptual understanding and certain problem-solving skills. Further, Robertson (1990) found that learners' cognitive structure is also a strong predictor of transfer problem-solving performance in physics.

LIMITATIONS OF CONVENTIONAL TOOLS ON PROBLEM-SOLVING PERFORMANCE

Even though there are significant advantages for developing knowledge maps to support problem-solving, there are several significant limitations of existing knowledge map construction tools. First, conventional knowledge maps are designed to create explicit organization of *conceptual* knowledge (Stoyanov & Kommers, 1999). The conceptual knowledge that is a part of human knowledge representation systems denotes facts, concepts, and objects. However, problem-solving performance requires both conceptual knowledge and *procedural* knowledge (Hegarty, 1991). That is, a learner should develop associative processes as well as elaborate a variety of concepts retrieved from prior knowledge to support problem-solving performance. For example, when a mechanic repairs an engine problem in a car, s/he may follow defined routine processes to fix the problem. At first, she or he tries to listen to the noise coming from the engine and then, inspects a switch system of the engine by manipulating computer equipment (which requires procedural knowledge to operate). Depending on the symptom, the mechanic may change some parts or remove the engine from the car (a task that also requires procedural knowledge). As seen in this example, problem-solving performance is basically a process-oriented activity that is aided by conceptual knowledge (Lesgold, & Lajoie, 1991).

Second, conventional knowledge maps do not sufficiently represent the *context* of a given problem. Here, contextuality denotes the meaningfulness of the situation as interpreted through a learner's prior knowledge and experience. When drawing a conventional knowledge map, learners employ the properties of such mapping procedures as (a) enclosing the concepts in boxes, ovals, or circles; (b) drawing links as bi-directional or uni-directional lines; and (c) constructing labels or annotations that appear in a text description to denote the relations among concepts. While the links in the knowledge map provide some opportunity to express the context of a problem by allowing learners to interrelate the concepts in multiple ways, the annotations that indicate the relations (e.g., words such as "via," "are," "e.g.," "has") do not meaningfully describe a situation. Even more elaborate annotations such as "usually causes" or "sometimes predicts" fail to describe the full context of the learner's understanding of the context. Thus, the space available for elaboration of the context is a severe limitation. (See the third limitation, listed, for further discussion of space limitations.) In other words, the conventional knowledge map seems to be an "abstract archetype" of the situation and thus facilitates more abstract and de-contextualized knowledge construction while problem-solving.

For instance, if a learner connects a concept to another concept and depicts their relationship with a label such as "is," other learners may not fully understand why these concepts are interrelated. Furthermore, the simple requirement of labeling the link between concepts does not require much individual reasoning about the nature of the relation between concepts, yet such reasoning about the context of the problem is necessary to facilitate effective problem solving (Norman & Schmidt, 1999). This need for learners to solve problems in context is critical and several problem-solving researchers have focused much of their attention in this area: specifically, through designing real everyday problems and focusing on the transfer of problem-solving skills to new contexts (Sinnott, 1989).

Third, the number of representable concepts on a computer screen or paper is limited and may prevent a learner from expressing his or her thoughts as fully as he or she could if sufficient space were available. In other words, it may be impossible for learners to fully represent their conceptual knowledge due to spatial limitations. Even though specific and comprehensive representations add complexity to the map, they support learners in externally storing larger number of nodes. This facilitates interrelating what is already known with what is newly acquired, and restating their understanding (Hegarty, 1991).

In addition to the number of concepts represented, the quality of the represented concepts should be also considered. Let's assume that the two concepts A and B are linked in a knowledge map. If concept A seems to be close to concept B visually, does that mean the concept A is conceptually very close to the concept B? Unfortunately, the physical distances between the concepts, which are represented visually, are not usually correlated to conceptual distance, given spatial limitations. If the physical distance between two concepts could represent the conceptual, or internal, strength of association between them, that would add to the value and meaning of the knowledge map. Further, it would facilitate learners in focusing on the significant operators of the problem, helping them move from the initial stage of defining the problem space to the later idea generation stage (Larkin, 1989; Stoyanov, 1997). It has been argued that annotations attached to a concept, or relatedness, which indicates the conceptual distance numerically, can supplement the limited description of relations among the concepts represented

(Schvaneveldt, 1990 as cited in Fisher, 2000a; Scaife, & Rogers, 1996). However, the main purpose of annotation usage is not so much the description of distance as defining the meaning of the concept. In addition, this kind of "numeric distance" may encourage learners to infer, perhaps erroneously, the relative the conceptual distance, without providing any reliable scale to clarify that distance.

Fourth, although recently developed computer-based tools support learners to portray their knowledge representation in forms of animation, moving image, and audio (e.g., *Mind manager, Inspiration™, Decision explorer,* and *SemNet*), most conventional knowledge maps support learners in representing context through modalities of text and graphics. However, multiple representations of information (e.g., the "multiple modality effect") may be better than only one representation to support learning (DeJong et al., 1998; Najjar, 1998). Problem-solving performance may require the use and integration of multiple forms of representation (Boshuzien & Schijf, 1998; Mayer, 1999). Thus, if a learner had the option to represent information through text, visual, and/or animation, s/he may seek possible operators more easily, as well as transfer what was learned to a new problem more effectively.

Overall, there is a need for new principles to guide the design of knowledge map construction tools that support problem solving. The next section will suggest five new design principles for this purpose.

DESIGN PRINCIPLES FOR A KNOWLEDGE MAP CONSTRUCTION TOOL TO SUPPORT PROBLEM SOLVING

Given the limitations of existing knowledge map construction tools for problem solving, five design principles emerge. The rationales and basic assumptions of these principles follow.

1. Combinational representation principle: *Conceptual and corresponding procedural knowledge should be represented together rather than separately.*

The combinational representation principle is based on the idea that problem-solving performance can be improved when the learner can selectively access and manipulate both conceptual and corresponding procedural representations (Anderson, 1983; Mayer & Wittrock, 1996). Unlike conventional knowledge maps that focus on concepts, or flowcharts that focus on processes, the combinational representation principle emphasizes that the creation, modification, and removal of conceptual knowledge based on corresponding procedural knowledge must be supported.

The rationale for this principle is supported by empirical research in several areas. Anderson (1983) in the ACT theory claimed that procedural knowledge could be obtained by making inferences from the declarative knowledge that deal with factual information. In addition, Jonassen, Beissner, and Yacci (1993) argued that procedural knowledge should be based on conceptual knowledge because no action can be performed without the awareness of necessary conceptual information for performing a given procedure. Thus, the learner must elicit structural knowledge, knowledge about the relations among concepts, which mediates the necessary declarative knowledge for activating procedural knowledge for solving complex problems. This idea has been also supported by problem-solving researchers such as Hegarty (1991) who proposed that problem-solving performance is affected by both conceptual and procedural knowledge.

2. Contextual enhancement principle: *The learner should provide information regarding the context of the problem.*

The contextual enhancement principle is based on the idea that problem-solving performance is a context dependent activity (Jonassen, 2001). Thus, concepts represented in a knowledge map should reflect the learners' individual context and meaning by which they interrelate them. By including information about their individual contexts related to the problem, learners can better communicate to others how the concepts are meaningfully situated. Moreover, it is advantageous for learners to describe the context as it aids in their metacognitive understanding of the problem-solving process (Jonassen, 2000).

This principle is based on the idea of case and theme commentaries as described in Cognitive Flexibility Theory (Jacobson & Spiro, 1995). Commentaries, which are a description of the relation between the case and theme, provide short explanations of how a concept is related to different concepts and situations. Although the concept in itself seems to be abstract, it becomes meaningful when the commentary is attached between the concept and the case. For problem solving, the addition of the commentary would enhance understanding of the learner's context and meaning regarding the problem by including personal experiences and prior knowledge.

3. Spatial flexibility principle: *The space where learners represent concepts should be flexible and not artificially constrained.*

The spatial flexibility principle stems from the premise that learners solve problems better when they can represent their concepts as fully as necessary (Hegarty, 1991). However, when concepts are represented on paper or on a screen, due to space limitations learners may not be able to represent all the concepts or processes they find relevant to solving a given problem. To compensate for limited space, knowledge map construction tools generally allow the learners to manipulate the scroll bar and to employ a zooming function. Unfortunately, the greater the number of concepts, the more complex is the overview of the knowledge map, and the more difficult it becomes to view the entire representation (Jonassen, Reeves, Hong, Harvey, & Peters, 1997).

It is also worth considering n-dimensional (as opposed to 2-dimensional) knowledge maps to represent as many concepts as necessary. Scaife and

Rogers (1996) argued that three-dimensional visual representations are better than two-dimensional representation for learning. The main characteristic of the n-dimensional knowledge map is the invisibility of the map. That is, the map exists internally, but is not fully represented externally (Fisher, 2000b; Scaife & Rogers; Stanton & Baber, 1994). The n-dimensional knowledge map can support learners in representing their knowledge without spatial graphical aids on the basis of "node design" principles (Stanton & Baber) or to construct a hierarchy of concepts and relationships (Fisher, 2000b).

4. Property association principle: *The magnitude of association between concept and associated processes should be classified.*

The property association principle is based on the idea that by classifying concepts by the relative association between the concepts and processes, learners could reduce the time required to search the knowledge map for important information and more easily represent problems internally (Jonassen et al., 1997; Stoyanov, 1997). The magnitude of association between concepts and processes is based on the number of shared properties. In other words, the more properties the concept shares with a process, the greater magnitude of the relation between relevant concepts and the particular process. For instance, Fisher (2000a) described how a screwdriver could share more properties with the process of repairing a car than with the process of cleaning the windows. To show the magnitude of associations explicitly, she suggested that each concept be rated on a scale from 1 (not at all) to 5 (highly related).

This principle is based on methods of object-oriented programming (Stanton & Baber, 1994). An underlying assumption of object-oriented programming is to enhance the speed of programming by sharing objects. Similarly, the purpose of a knowledge map is to accelerate the learner's access to relevant information for solving a problem. The knowledge object is the smallest representation of knowledge that can be shared with other knowledge objects and with other learners because of their common embedded properties. The properties of objects characteristic of programming concepts, such as inheritance, polymorphism, and propagation, are also applicable to external representations of learner's internal representations (Merrill, 1993; Stanton & Baber, 1994). In short, the association between a concept and process is determined by the quantity of properties shared between them.

5. Multiple representation principle: *Concepts should be represented through multiple modalities.*

The multiple representation principle is based on the idea that effective problem solving is dependent on learner construction of mental representations that contain elements of knowledge, representational formats, and symbol systems (Tergan, 1997), and that these internal mental representations are facilitated through multiple external representations (Bauer &

Johnson-Laird, 1993; Jonassen, Beissner, & Yacci, 1993; Zhang, 1997). This principle is based on dual coding theory (Paivio, 1990), which proposes that multiple representations enable learners' problem-solving performance by providing learners with ways to integrate two or more forms of the information through multiple information processing channels. Vekiri (2002)'s meta-analytic study of dual coding theory indicated that multiple representations helped learners to link visual and verbal information, resulting in improved problem-solving performance (Mayer, 1999).

A NEW KNOWLEDGE MAP CONSTRUCTION TOOL FOR SUPPORTING PROBLEM SOLVING

A new tool for supporting knowledge map construction during problem solving was developed based on these five principles. The tool consists of four main components as illustrated in Figure 2: (a) interface; (b) templates; (c) knowledge database; and, (d) a user-driven database. The learner may enter properties and values into a template through the interface of the tool to create a new template. Conceptually, templates have two components: template A, which temporarily stores the information that the learner inputs, and

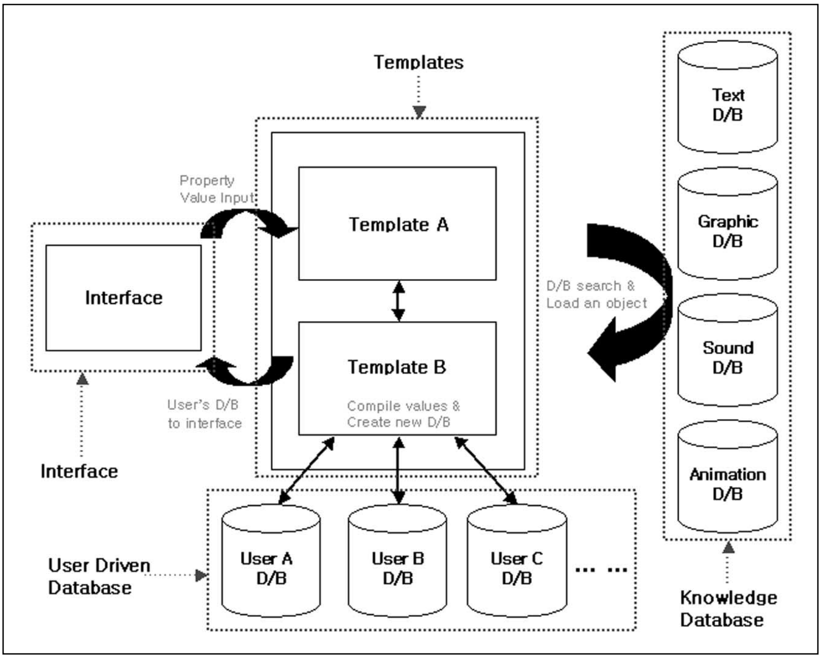

Figure 2. The architecture of the tool

template B, which saves the final information in the user-driven database. The conceptual difference between template A and B depends on whether or not the learner decides to save the information in the permanent database.

The learner is able to search concepts, whether in the permanent or temporary files from the knowledge database. The knowledge database could be preloaded with objects or it could begin in the empty state. The knowledge database allows the learner to represent this information in the form of animation, graphics, audio and/or text. The learner can choose one of these four modalities and load the concept as an object to template A from one of four sub databases: the text database, the graphic database, the audio database, or the animation (video) database. The information defined by the learner is stored in template A again. For team problem solving, the external representation of a single learner can be displayed and the team can collaborate to develop a shared mental model of the problem space, along with a jointly developed solution to the problem.

The interface includes five main elements: (a) menu and tool bar, (b) task title window, (c) task description window, (d) property window, and (e) main window (see Figure 3). The menu bar for a given “File” is used to open a previously saved template, save a new template, or close the currently open template. Another feature of the menu bar, “Help,” is designed to suggest just-in-time information for using the tool. The tool bar also has the same functions to the menu bar as well as additional functions to select a process represented in the main window.

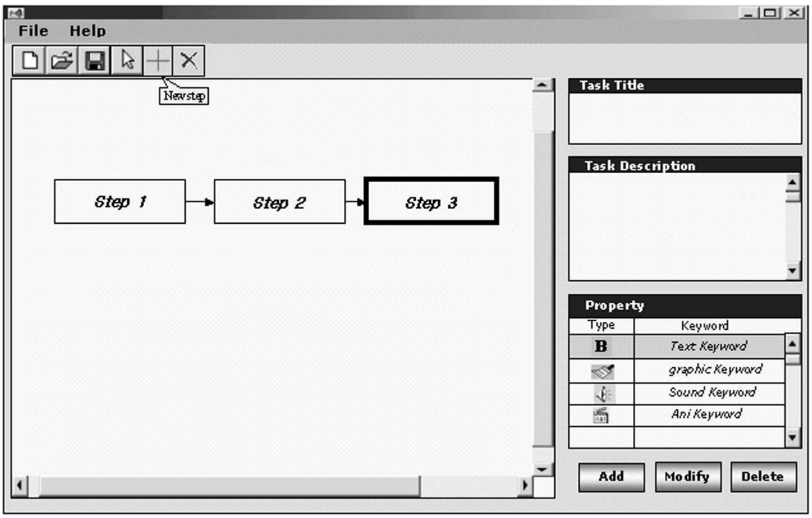

Figure 3. The interface of the tool

The task title bar is used to specify the name of the template (e.g., [filename].inn). The task description window helps the learner develop a richer knowledge map by describing the relations between a concept and a process. From these problem descriptions, other learners can understand the reasons why the learner identifies and elaborates the concept in the problem and why this concept is associated with the process. In short, the problem description window was designed to support the contextual enhancement principle.

The property window, accessed by the main window is used to add, modify, and delete a concept in terms of type and keywords. The types of the concept can include text, graphic, audio, or animation (video) and thus support the multiple modes of representation principle. The property window also addresses the principle of spatial flexibility. Although there is no physical linkage represented by a line between the concept and the process, the connection is represented as a conceptual link as displayed by the association bar and property window. Additionally, this n-dimensional linkage may overcome the limitations of space where the concepts can be represented. The learner then links the concepts to as many processes or concepts as are relevant by clicking the "Add" button.

If the "Add" button below the property window is clicked, the "Selection" window in Figure 4 pops up. The Selection window allows the learner to select keywords that are connected to the types of information as well as to the process represented in the main window. The retrieved concepts and the processes with which concepts are associated are combined to reflect the general mechanism of problem-solving performance (Mayer & Wittrock, 1996).

The association buttons, as part of the keyword, enable the learner to manipulate the magnitude of properties between a process and a concept. For example, the fact that the magnitude of properties is high means that the concept shares a lot of properties with the process as well as plays a significant role to move the current problem-solving process toward the next process. In short, this association bar reflects the principle of property association. The context of problem in terms of concepts is described in detail in the keyword description box.

The procedure that learners should follow includes six steps: (a) describe the keyword that represent the source of the information explicitly; (b) select one of the association buttons; (c) describe the reason why this concept was related to the process in light of personal knowledge and experience, and how this concept relates to possible solutions of the problem; (d) choose one of four modes of information; (e) select the source of the information from one of four types in the Knowledge base; and (f) close the Selection window.

In Figure 4, "Preview" of the information provides an example of selecting an animation to represent a learner's internal knowledge structure. As soon as the learner selects the animation radio button and chooses a file from

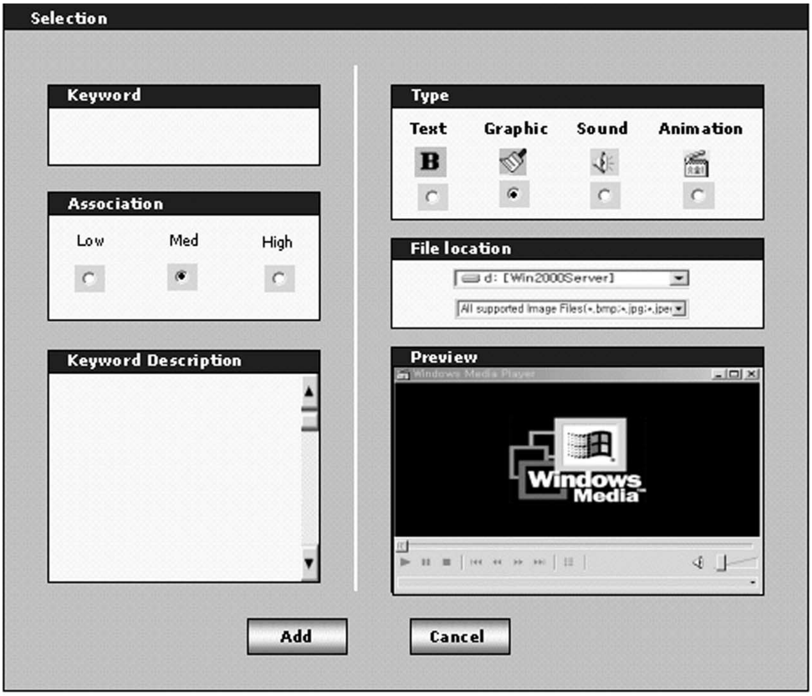

Figure 4. The selection of information from Knowledge database

the Knowledge database, the Window Media Player™ appears to demonstrate the contents of the file.

Once the representation is selected, a learner saves his or her template in the User-driven database. The User-driven-database is designed to store the learner's product of representation and is automatically constructed as soon as the learner saves his or her template by clicking either "Save" in the menu bar or a save button that looks like a diskette in tool bar. Other students can retrieve the external representation of the learner for a problem solving from a remote distance because the User-driven-database is stored on a Web server. By storing assets in a database that is open to any user (shared with "Everybody" in the shared library), even learners who are not users of the tool can access useful information for problem-solving projects.

CONCLUSION

Overall, this tool is expected to enhance learner problem solving by allowing them to combine concept and process, present the contextuality of the problem, go beyond the limitations of two-dimensional representational space, classify concept/process associations, and facilitate multiple modalities while constructing a knowledge map. Furthermore, learners can use the tool as a working portfolio of compositions for purposes of reuse and exhibition. The learner's ability to use the tool, and to use other techniques for representing, organizing, and reusing knowledge objects, would develop throughout the use of the tool. While the design principles were derived from previous research and theory, empirical studies are necessary to test the effectiveness of them as employed through the new tool in comparison with conventional knowledge-mapping strategies and tools. If empirical studies reveal that the tool is more effective than conventional strategies, further refinement of the tool can be explored and tested. The end result could be a tool that optimizes the external representation of internal representations to enhance problem solving.

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