STUDENTS' CONCEPT PATTERNS REVEALED BY COMPUTER ANALYSIS OF LANGUAGE-CONSTRAINED SCIENCE CONCEPT MAPS

by

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**Dedicated to
Virginia R. Kleeberger
and the Memory of
Anthony H. Kleeberger
with the Love and Gratitude
of Their Daughter**

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CHAPTER I

INTRODUCTION

Overview

Cognitive research into how young students learn science underlies current science education reform efforts. The American Association for the Advancement of Science Project 2061—*Science for All Americans* (AAAS, 1989) report recognizes that students' existing ideas influence new learning, and that misconceptions or naive preconceptions that impede understanding must be identified and challenged. The report advocates that schools focus on a few concepts presented in a variety of contexts since a variety of experiences is more likely to embed the concepts in the student's knowledge structure and deepen understanding. The National Science Education Standards (1996) map for classroom science an integrated approach that presents unifying concepts in multiple contexts, interlinks concepts, and, in a learning spiral, revisits concepts in greater complexity and abstraction as the student progresses through grade levels. The National Science Teachers Association and National Science Foundation support The Scope, Sequence and Coordination Project (NSTA, 1995) that implements a standards based interdisciplinary strategy for high school science that includes goals of interrelating basic concepts and principles while taking into account prior knowledge and preconceptions. One goal of scientific literacy is achieved through the acquisition of a complex, interconnected knowledge of science (Michigan School Board, 1991).

It is difficult to determine the extent to which students understand the connectedness of ideas. Standardized tests tend to measure understanding of isolated facts. For students who have verbal facility and good writing skills, essays can demonstrate ability to organize related ideas; however, difficulties with verbal expression can mask understanding. Concept maps are recognized as an effective representation of interconnected knowledge. Prior studies support concept mapping as a tool to assess student understanding of the complex framework of knowledge (Regis & Albertazzi, 1996; Pendley, Bretz & Novak, 1994; White & Gunstone, 1992; Beyerbach, 1990; Moreira, 1987). An advantage of concept mapping is that it uses language sparsely, focusing only on the ideas and how they relate to one another. One interdisciplinary science course for pre-service teachers uses concept maps to help students "clarify and organize relationships among science concepts" (Ramsey, Radford, and Deese, 1997). The visual representation of the concept map shows the student's organizational framework and represents the student's understanding of interrelationships in a domain.

While concept mapping is a valuable tool, in practice, concept maps can be very time-consuming for students to generate, and time-consuming and challenging for teachers to evaluate. This research applies technology to improve the efficiency of the concept mapping process and offers a new approach for the evaluation of concept maps that may provide useful insights into students' thinking about a domain. While a traditional approach to concept mapping focuses on each student's unique expression of ideas, students who have experienced a similar curriculum may be expected to show some commonalities in the way they see ideas connected. This research proposes a methodology for the evaluation of concept maps that 1) compares large numbers of individual concept maps, 2) clusters groups of concept maps that represent interconnections in a similar way, and 3) generates composite concept maps to show patterns in interconnections. Before this research can compare large numbers of student concept maps and consolidate groups of similar maps, three concerns must be addressed:

the construction of maps that permit comparison, the efficiency of data collection, and the method of identifying similar concept maps.

The first concern is resolved by the use of language constraints that provide a tool box of components for map construction and enable the direct comparison of concept maps. In support of using language constraints, some students may choose some of the same words for concepts and linking phrases for freely-drawn concept maps of a domain, and rich variations of synonyms are commonly found among student maps (Novak & Musonda, 1991). If students sometimes choose words that are similar, they may agree on the usage of a set of terms related to the domain. Prior research supports the use of lists of concepts and linking phrases for concept mapping (Regis & Albertazzi, 1996; Novak & Gowin, 1984). Dansereau and colleagues have done extensive research in the use of constrained language in semantic maps (Jonassen, Beissner, & Yacci, 1993). If all students use the same construction set of concepts and linking words, then technology may be used to compare those language-constrained concept maps.

The second concern stems from challenges associated with traditional methods of constructing concept maps that limit the application of concept mapping in classroom practice. Concept maps can be very time-consuming to generate for students, and the topology of concept maps makes them challenging to evaluate for teachers. This concern is resolved by the use of computer-assisted concept mapping to improve the efficiency of constructing concept maps and collecting data for evaluation.

The third concern is the need for a method to identify similar concept maps. Traditional methods of evaluating concept maps focus on scoring individual maps. Freely drawn concept maps may be compared to a referent or criterion map, or scored on the basis of structural features, but traditional scoring methods do not imply congruence between maps with the same score. Similar map scores may indicate that the overall quality of the maps is comparable, but the ideas represented may be disparate. This concern is resolved by the use of language-constrained concept mapping and direct comparison of similarities between concept maps. Goldsmith and Johnson (Schvanevelt, 1990, chap. 17) note that students can be discriminated on the basis of comparisons between students. The similarity measures that quantify the similarity between pairs of maps can be used to identify groups of students who share similar ideas about interrelationships within a domain. Between-group comparisons can be used to order groups by level of represented understanding; moreover, comparison to an expert map is not necessary to establish relative levels of understanding.

The information that can be extracted from the composite maps of groups of similar concept maps may be valuable to the teacher. Since the comparisons include all connections between concepts, and not just the accepted connections, the composite concept map for each group can reveal alternative conceptions that may hinder new learning. Missing concepts and links may indicate gaps in understanding that are crucial to the understanding of new concepts. The composite maps may also show strong fundamental interconnections that represent the shared conceptual framework of the group. If true, such findings may have relevance to instructional planning and curriculum design.

This research develops a method of constructing and analyzing concept maps to discriminate students on the basis of their understanding of the domain, to identify groups of similar maps, and to ascertain levels of understanding of a domain. Several technological tools are utilized in the map construction and analysis processes. The Computer-assisted Concept Mapper (CCM), developed explicitly for the proposed work, is a software tool for the construction of language-constrained concept maps. CCM provides a visual mode and concrete props for student generated concept maps. Using CCM, students arrange given concepts and linking words to show relationships among them. The Concept Map Analysis Tool, also developed for this dissertation, is a hypercard stack that compares similarities between pairs of student concept maps. These similarities become the basis for cluster analysis that identifies groups of similar maps. A composite map of each cluster, generated by Pathfinder's Knot-Mac program (1992), provides a graphic display of the interconnectedness of ideas, and, most importantly, places relations in context. Finally, a comparison of the composite maps looks for patterns of increasing complexity and developing understanding of the domain.

As students progress through a curriculum in successive grades they have different experiences and develop more complex mental schema. When students in successive grade levels who have experienced a similar curriculum develop concept maps of a set of ideas, their maps should reveal increasing depth and scope of understanding and show a continuity in knowledge development in the specific domain. This research applies the methodology to concept maps of a large number of sixth, ninth, and twelfth grade students who have experienced a similar science curriculum, in a school learning environment. Concept maps of cross-age students are analyzed to discriminate levels of understanding of the domain and to seek a continuum of understanding as the students progress in school learning.

Before this technological approach to concept mapping can be used, the research must first establish the validity and reliability of language-constrained computer-assisted concept mapping. The research then proceeds to assess whether computer analysis of the language-constrained computer-assisted concept maps can differentiate between students who are at various points of conceptual understanding of a domain. Finally, the research looks for a continuum of developing understanding in two ways, first, by comparing clusters of similar concept maps for all students; and second, by examining composites of grade-level concept maps for evidence of progressive learning within a specific science domain for students in grades six, nine, and twelve in a school learning environment. The science domain selected for this dissertation research is the water cycle, based on an expectation that more complex interrelationships of the water cycle should be learned as students advance through the K—12 science curriculum.

Statement of the Problem

The purpose of this dissertation is to identify patterns in the understanding of a science domain for a large number of cross-age students using a technological approach to the construction and evaluation of concept maps. The goal is to learn whether there are commonalities in the way students represent ideas in a domain, and whether a progression in learning is evident in cross-age concept maps of students who have experienced a similar curriculum. Before this research can be presented, the validity and reliability of the language-constrained Computer-assisted Concept Mapper software tool must be established, and the ability of Concept Map Analysis to discriminate students on their knowledge of the domain must be confirmed. Therefore, two purposes focus the research of this dissertation: 1) to demonstrate that constrained concepts and linking words can be used to produce valid computer-based concept maps that can discriminate students on their knowledge of the domain, and 2) to discover patterns in the continuum of conceptual understanding that may emerge from comparisons of student concept maps.

This dissertation is organized by two research questions that serve the purposes of the research. The first question is answered by a series of three studies related to the use of language-constrained computer-assisted concept mapping to identify students at different levels of understanding. The second question is answered by a fourth study that looks for evidence of a continuum of learning as conceptualization of the domain becomes more complex. The structure of the dissertation is further elucidated in the next section.

Question 1

The first question asks: can constrained concepts and linking words be used to produce valid computer-assisted concept maps that can discriminate students on their knowledge of the domain? This question is answered by three studies: a test of validity, a test of reliability, and a discrimination study.

Study 1: The Test of Validity of Language-constrained Computer-assisted Concept Mapping.

This study seeks to demonstrate that, for a given domain, when no intervening instruction occurs, concept maps constructed with the computer-assisted mapping tool are similar to concept maps produced by students using pencil and paper techniques. This study asks the question: does the student when using the computer assisted concept mapping tool generate concept maps comparable to those produced using pencil and paper techniques?

Analysis

Structural components of language-constrained pencil and paper and computer-assisted concept maps are compared to show similarities between the two types of maps.

Study 2: The Test of Reliability of Language-constrained Computer-assisted Concept Mapping.

This study seeks to demonstrate that, for a given domain and when no intervening instruction occurs, the concept maps produced by students using The Computer-assisted Mapper are reliable and consistent over time. This study asks the question: does the student when using the language-constrained computer-assisted concept mapping tool generate similar concept maps over time?

Analysis

Structural components are compared for two sets of language-constrained computer-assisted concept maps to show similarity in maps produced over time by the same students.

Study 3: The Test of Discriminating Ability of Language-constrained Computer-assisted Concept Mapping.

There are two aspects to the study of the discriminating ability of language-constrained computer-assisted concept mapping. This study seeks to demonstrate 1) that students' language-constrained computer-assisted concept maps will reflect their level of understanding of the knowledge domain; and 2) that students will show a similarity between their concept map and that of other students of the same competency level as evidenced by the structural components of their maps. Overall, this study asks the question: can computer analysis of language-constrained computer-assisted concept maps discriminate students on the basis of their knowledge of the domain? To fully answer this question, both aspects of the study will be examined.

The first aspect of this study focuses on whether comparison of language-constrained computer-assisted concept maps on the basis of structural components such as concepts used, concepts connected, linking phrases, and directionality selected in representing relations can identify groups of maps that show evidence of different levels of understanding of the domain. This aspect of the study will answer the question: can clusters of similar maps be identified on the basis of their structural components?

The second aspect of this study looks for evidence that similar maps are produced by students of the same level of competency. Level of competency is expected to increase with grade level, although a range of competency is expected among students at each grade level. This aspect of the analysis asks: do students of the same level of competency show similarities in the structural components of their concept maps?

Analysis

This study compares the structural components of concepts used and concepts connected for pairs of student concept maps. All student concept maps are differentiated on the basis of similarity calculations to identify clusters of similar maps. Identification of clusters confirms the ability of the tool to differentiate students on the basis of their represented schema. When trying to show that students of the same competency level produce similar concept maps, two approaches are used. In one approach, the clusters composed of similar maps are examined to show the distribution of students by grade level across clusters. In the other approach, the concept maps of each grade level are analyzed for patterns in structural components such as concepts used and concepts connected; these patterns are then compared across grade levels for evidence of differences in levels of understanding.

Differences in concept maps are expected, based simply on the uniqueness of conceptual schema. In a cross-age study that relates to a segment of the curriculum, concept maps are also expected to reveal different levels of competency in the domain. As learning develops across grade levels, continuity in learning may be evident in concept maps. The second purpose of this dissertation is to show that a progression in learning in a domain is revealed in concept maps generated by cross-age students who have experienced a similar curriculum.

Question 2

The second question that this dissertation asks is: does the comparison of clusters of similar language-constrained computer-assisted concept maps reveal patterns in the continuum in understanding of the domain? This question is answered in Study 4.

Study 4: Evidence for Progressive Levels of Understanding of the Domain

Study 4 looks for a continuum in understanding shown in the patterns of knowledge structure represented in concept maps of the domain. Question 2 generates two parts to Study 4. In Part One, composites of clusters of similar maps across all grade levels are analyzed; in Part Two, composite maps of each of the three grade levels are analyzed.

Before a continuum in understanding can be recognized in a series of map clusters, characteristics that indicate increasing complexity are used to order clusters of concepts maps. To get to that point, several questions must be answered. What distinguishing patterns in structural characteristics are identified in composites of clusters of similar concept maps? What is the scope of the common core of knowledge? What structural characteristics may indicate greater complexity of the composite concept maps? What patterns indicate a progression of learning across clusters of similar maps? Part One of this study seeks to demonstrate that clusters of similar concept maps across grade levels can be ordered on the basis of structural characteristics to show a progression of developing understanding in patterns of knowledge structures representing the domain.

Part Two of this study addresses the relationship of grade level to level of understanding and asks: is there a difference in the scope of the common core of knowledge and the complexity of the connections within concept maps as students progress through schooling, namely in a comparison of sixth, ninth, and twelfth grade students' maps of the same domain? Part Two seeks to show that for sixth, ninth, and twelfth grade students, a comparison of composite concept maps of a domain will indicate an increase in the scope of the common core framework, increased complexity of the connections over time, and a continuum of understanding.

Analysis

The data set for Study 4 is the same as obtained from the discrimination Study 3. No additional data collection is necessary.

Earlier studies by Novak and colleagues have shown an overlap of expertise between grade levels, particularly when the learning at earlier grade levels provides a framework for later learning. Therefore, Part One of Study 4 further examines the clusters of similar concept maps of all students that were identified in Study 3. The composite maps representing each cluster of similar maps are analyzed and ordered to determine whether map characteristics provide evidence for a progression of learning. The scope of core concepts and the complexity of the composite maps are examples of characteristics that may be used to infer levels of understanding of a domain. Continuity of learning is explored by comparing clusters ordered by similarity to the cluster representing the highest level of understanding of the domain.

Part Two examines the relationship of grade level to an increase in understanding of the domain. Part Two first analyzes the grade level distribution across the ordered clusters to see whether the patterns of increasing scope and complexity coincide with an increase in grade level. Finally, Part Two compares the composite maps of each of the three grade levels for evidence of developing understanding.

A comparison of composite concept maps for cross-age clusters of similar maps for a specific domain of knowledge may be expected to reveal traits of progressive learning in the domain such as increasing scope of relations, greater cohesiveness of relationships, decreasing insularity of relations, and increasing connectedness of core concepts. A comparison of composite concept maps of each grade level, sixth, ninth, and twelfth, may also reveal evidence of progressive learning; however, overlap in understanding of the domain is expected that may diminish differences between grade levels.

Resources

Two computer-based tools were developed for use this in this dissertation research, The Computer-assisted Concept Mapper (CCM) and the Concept Map Analyzer. The current version of CCM is written in C++ and requires a computer running Windows 3.1 or above. A networked computer lab environment is advantageous to collecting large numbers of maps for analysis. The first analysis tool, the Concept Map Analyzer used to compare similarities between concept maps, is a Hypercard stack that requires a Macintosh computer. Subsequent analysis utilizes SPSS (1996) and/or SYSTAT (v5.2.1, 1992) for cluster analysis and other statistical comparisons. Finally, Knot-Mac is used in this research to create the visualizations of the composite maps representing each cluster. A brief overview of CCM is presented in the next section. Further description of the functions of CCM in generating language-constrained concept maps is found in Appendix A.

Computer-assisted Concept Mapper (CCM)

The Computer-assisted Concept Mapper provides students with a "toolbox" of concepts and linking terms to construct a concept map. Using CCM, the instructor provides a list of about twenty to thirty concepts and as many as ten linking phrases. The student uses CCM to arrange the concepts on the monitor, connecting the concepts with directional arrows. The student then selects from the linking phrases provided the linking phrase that she thinks best describes the relationship between the concepts, and drags the phrase to the empty box on the arrow between the concepts connected. A sample computer screen is shown in Figure 1.1.

When the student saves the map, the computer program converts the topology of the concept map to a list of triads. The encoded list of the related concepts and links, might be, for example, 1A3, 1B5, 3C2, with one triad per line in the file. This first step in the disaggregation of the concept map makes possible numerous computer-based comparisons of the structural components for large numbers of concept maps.

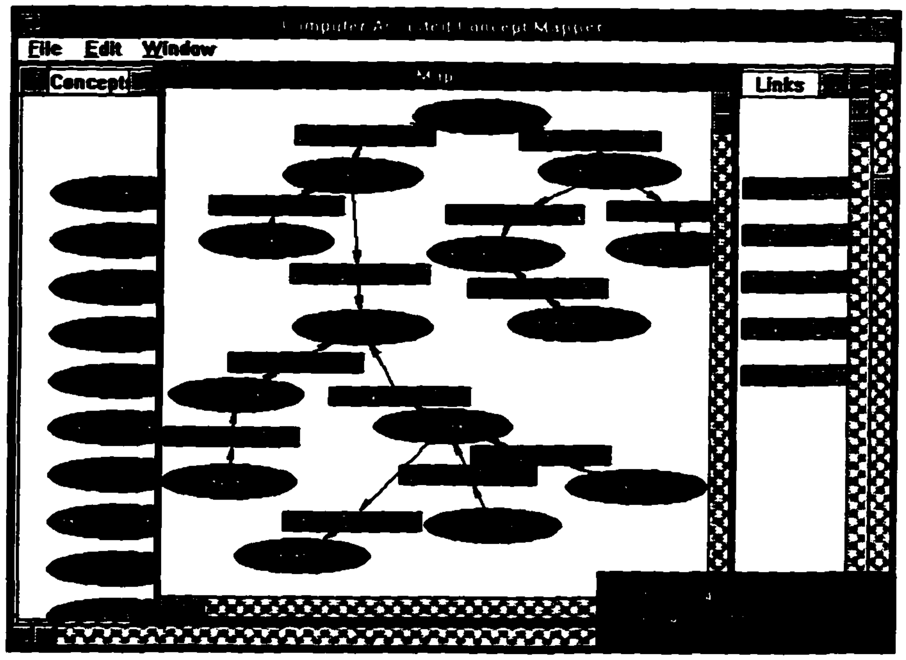

Figure 1.1. A sampie Computer-assisted Concept Map screen showing the Concept Corral, Map window, and Link Corral that students used while constructing concept maps.

Concept Map Analysis Tool

The concept map analysis tool is a hypercard stack that in a given set of concept maps compares all pairs of maps on the basis of specified structural features and calculates a ratio of the similarity between them. The resulting matrix of similarity measures for all concept maps compared is then analyzed to produce clusters of similar maps.

Summary

One aspect of scientific literacy is demonstrated when students organize and represent the complex interrelationships between science concepts of a domain. Chapter One has presented the use of computer-assisted concept mapping to probe the understanding of a domain for large numbers of students. If concept mapping can be used to identify what it is that most students know or do not know in the context of the domain, instruction can be designed to build on the framework of prior knowledge. Inspection of composite maps may identify gaps in knowledge that must be remedied before meaningful learning can occur, as well as shared knowledge that can be used to anchor new learning. The analysis of large numbers of student concept maps may also help to evaluate the effectiveness of curriculum components.

While concept mapping is a powerful tool for representing the way students see ideas connected, the traditional method of interviewing students, hand-drawing concept maps, and hand-scoring concept maps does not extrapolate well to large-scale evaluation of student understanding. The proposed computer analysis of language-constrained concept maps has two benefits: first, it allows for direct comparison of student maps; and secondly, it preserves the essential context of the relationships within the framework, delivering a visual of the cohesiveness of the composite structure.

When extended to a cross-age study, this direct comparison and composite representation of concept maps for a given domain is expected to provide information about the development of student understandings of interrelationships within the curriculum area. Levels of student understanding should be discriminated. A comparison of composite concept maps spanning sixth grade, ninth grade, and twelfth grade students for a specific domain of knowledge may be expected to reveal traits of progressive learning such as a continuity of learning, increasing scope of relations, greater cohesiveness of relationships, and increasing connectedness of core concepts.

This research seeks to discriminate levels of understanding of a specific science domain and to discover a progression of understanding of the domain as students progress in school learning. This is accomplished through the comparison of a large number of concept maps of cross-age students who have experienced a similar curriculum. Chapter Two will provide the background of prior research that supports the evolution of this approach to concept mapping.

CHAPTER II

REVIEW OF THE LITERATURE

Overview

This dissertation is about the use of language-constrained computer-assisted concept mapping to probe student understanding of a specific domain. Cross-age comparisons of students who have experienced a similar curriculum may be expected to provide a window on the development of understanding of the specific domain within the context of the curriculum. This dissertation compares large numbers of student concept maps to reveal a spectrum of understanding of a domain that smaller samples of students could not show as clearly, as accurately, or in as fine-grained discrimination.

To provide a background for the dissertation, this review is presented in three parts. Part One reviews the relationship of concept mapping to cognitive theory and knowledge development. Research that has probed the knowledge structures of novices and experts are reviewed for clues to the differences that might be expected for students at varying levels of understanding.

Part Two reviews traditional and technological methods of generating concept maps and semantic networks. The development of concept mapping is reviewed to show that concept maps probe cognitive processes and understanding. An important part of this discussion is the use of language-constraints in mapping tasks that facilitates the comparison of the concept maps or semantic networks. The benefits of working with a virtual map versus paper and pencil are discussed.

Part Three presents evidence to support the validity and reliability of concept mapping. Both traditional and technological approaches to the evaluation of concept maps and semantic networks are considered, including correlates and the use of referent structures in evaluation. The program SemNet demonstrates that some characteristics of concept maps can be measured objectively by the computer. In the last section, the analysis of Pathfinder networks provides an algorithm for the comparison of language-constrained concept maps. Graph analysis provides further support for the comparison of map similarities.

Part 1: Concept Mapping

The Representation of Knowledge Structures

The intricate web of knowledge structures can be more succinctly and effectively represented with graphical visualizations than with statements. Mapping of knowledge structures developed during the 1960's with techniques such as cycles and flow-charting. Concept mapping evolved in the 1970's as Joseph D. Novak and colleagues searched for ways to represent learning acquired through audio-tutorial lessons. Later popularized by Novak and D. Bob Gowin in Learning How to Learn (1984) as a way to manifest meaningful learning, concept maps have been used primarily, but not exclusively, in science education as an instructional, learning, and assessment tool.

Cognitive Theory and Concept Mapping

The development of concept mapping was influenced strongly by Ausubel's Theory of Learning that places concepts, and the propositions relating concepts, at the center of learning (Novak & Gowin, 1984). Concept mapping derives construct validity from its grounding in cognitive theory. Research by Novak and Gowin (1984) and

Ausubel (1968) suggests that concept maps mirror the cognitive processes of categorization, hierarchical concept structure, progressive differentiation, and integrative reconciliation, and represent the student's internal conceptual schema (Novak & Gowin, 1984).

In Ausubel's theory, students construct meaning from experience and build mental models to explain phenomena. The student links new concepts to fundamental underlying concepts that are part of the student's knowledge framework (Novak & Mussonda, 1991). Meaningful learning occurs when this prior knowledge interacts with new information to create a more differentiated and integrated conceptual framework. Knowledge structures of learners continually change as they develop understanding of the domain. Some characteristic changes in knowledge structures that might be expected as learners progress from novice to expert are discussed in the next section.

Novice vs. Expert Knowledge Structures

Several differences between novice and expert knowledge have been identified in the literature. Novices sometimes acquire pieces of information that are not fully integrated into the overall schema, and when a skill sequence is required, novices may at first string components together without a unifying organization (Royer, Cisero, and Carlo, 1993). The novice learner may see each step separately and approach the learning as rote memorization. Although learners acquire knowledge in increments, the process of knowledge construction is more complex than the simple accretion of facts

Ausubel's Theory of Learning, the basis for concept mapping (Novak & Gowin, 1984), describes knowledge acquisition as a complex series of mental processes. As learners progress, a hierarchical structure takes shape, and new concepts are integrated into the hierarchy. Sometimes a larger idea is introduced that requires previous hierarchies to be subsumed under the new hierarchical concept and reorganized in this new context. Progressive differentiation occurs as differences between concepts are developed by the addition of clarifying propositions and definitions. Integrative reconciliation occurs when two ideas that had been developed separately and are now seen to be related. Taken together these organizational processes serve to tightly integrate the knowledge structure. Expertise, then, should be marked by a shift from separate facts and clusters of information to a well-integrated and webbed knowledge structure. Supporting evidence was found in a cross-age study by Novak and Mussonda (1991).

A twelve year longitudinal study by Novak and Mussonda (1991) found that learners can move from a crude grasp of the domain to a more sophisticated grasp of the domain as they progress from the lower elementary grades through high school. Novak and Mussonda also found that the cross-age study showed a huge overlap in the conceptual sophistication of students at different age levels. Some younger children had more well developed concepts than less able students in upper grades. Novak and Mussonda concluded that even very young children can think profoundly, that complex learning about the nature of matter can begin in the early grades, and that fewer misconceptions appear to result if basic concepts are developed progressively from the early grades. Novak and Mussonda propose that the framework for the domain should be put in place in the early grades, so that the learner can build on a scaffold of fundamental concepts.

Chi, Feltovich and Glaser (1981) found that the expert learner generally represents more, and often different, relationships from those of the novice learner, but most importantly, that expert learners often use a more abstract framework to organize the same body of knowledge. In a study of how learners solve physics problems, Chi, Feltovich and Glaser (1981) noted that expert problem solvers apply the framework of subsuming principles of physics while novice problem solvers use a more superficial approach. Novice learners extract cues in the statement to visualize the problem, and then resort to a collection of definitions and rote formulas to solve the problem, often without success. In many domains the novice learner is found to operate from an alternative framework and holds the "wrong theory" (Goldsmith, Johnson, & Acton, 1991, p.93), and may even lack any real framework at all.

That learners operate from different frameworks was also observed in a biological problem solving task designed by Markham, Mintzes and Jones (1994) who found significant differences between college biology non-majors and majors. The learners drew concept maps that differed in extent, complexity and integration. The maps of biology majors showed strong restructuring using domain-specific super ordinate concepts, organizing mammals by reproductive and dietary patterns, while non-majors grouped mammals by anatomical characteristics and habitat. The preference for different frameworks was evident also in the card sorting exercise which was analyzed using multi-dimensional scaling techniques: while the majors sorted mammals by taxonomic groups, non-majors used superficial characteristics for grouping mammals.

Perhaps because of the difference in frameworks, the expert usually has a more holistic grasp of the domain that can be applied to problem solving while the novice deals inefficiently with small chunks of knowledge. Regis and Albertazzi (1996) report that students, using a limited number of guided choice terms to construct a concept map, showed evidence of cognitive reconstruction and a transition from specific terms to more subsuming terms in their post-instruction maps. Experts can more readily recognize patterns and deal with whole sequences, whereas novice learners focus on the details and take strategies one step at a time.

The observation of Chi, Feltovich, and Glaser (1981) that experts represent more concepts is reiterated by Nakhleh and Krajcik (1994) who found that important concept map characteristics such as concept clusters discriminate levels of learning within a domain. Individual relations and small clusters of related concepts are likely to be perceived by novices, while more advanced students demonstrate a broad scope of understanding. In maps of more advanced learners, critical concepts are more likely to be deeply embedded with links to many other concepts to a depth of at least two relations away from the focus concept. Although experts have more relations represented in their concept maps, expert maps are typically characterized by parsimony; novices on the other hand may add numerous relationships that do not contribute meaning to the hierarchy or other relations.

Aspects of the learner's mental schema and connectedness of ideas is externalized by concept mapping tasks. Concept mapping has been accepted as a valid and reliable a tool for instruction, learning, or assessment of interconnected knowledge.

Summary

The construct validity of the concept map flows from its foundation in cognitive theory. Concept mapping developed from Novak's effort to externalize the cognitive processes described in Ausubel's Theory of Learning (Novak & Gowin, 1984).

Knowledge structures continually change as learning occurs, and developmental levels of learning may be identified. Knowledge structures of novices and experts differ in several characteristic ways. Expert knowledge is marked by tightly integrated knowledge structures based on a framework of domain principles or organization while novice knowledge structures consist of loosely connected facts in a naive or superficial organizational framework for the domain. Deeply embedded key concepts characterize expert knowledge structures while novice knowledge structures are less dense. Expert knowledge structures generally have more and different relations than novice knowledge structures, yet expert knowledge structures are parsimonious. Expert knowledge exists as a web of functional relations, often built around the framework of the discipline. Novice knowledge characteristically lacks a framework, or is built around a naive framework.

The next section presents traditional and technological methods of generating concept maps and semantic networks and reviews challenges associated with the construction of concept maps.

Part 2: Construction of Concept Maps

Concept Maps as a Representation of Knowledge Structures

The Development of Concept Mapping

Novak sought a way to represent specific features relating to knowledge structures described in Ausubel's theory. In early attempts to identify these features Novak and Mussonda (1991) borrowed in part from Piaget's clinical interview methods. The interview protocol, although time-consuming, labor-intensive, and impractical for routine classroom assessments, remains a mainstay of traditional concept mapping research (Pendley & Novak, 1994).

The goal of the interview questions is to explore the information learned by the student, and the student's ability to relate and transfer that knowledge to new phenomena. Interviewers must be knowledgeable about the conceptual domain and are trained to ask probing questions to determine which cognitive statements or propositions are held by the student pre- and post-instruction. This technique led to listing the propositions extracted from the interview tapes and to "propositional analysis", but the student's perception of relationships between the various statements covered in the interview remained unclear. Novak's concept mapping tool evolved from the need to show how the students' concepts are linked over the knowledge domain.

The Structural Components of Concept Maps

Similar to other techniques for mapping structural knowledge that emerged in the 1960's, Novak's early concept maps linked concepts or ideas with lines. The ambiguity of links in the early maps was remedied when Novak introduced linking words to describe the relationships between concepts. This insistence on linking words sets Novak's concept maps apart from some other semantic maps, but the most distinguishing characteristic of traditional concept maps is their fundamental hierarchical structure. Even the earliest of Novak's concept maps followed the hierarchical arrangement placing subsuming concepts at the top of the hierarchy and specific assimilated concepts shown in Figure 2.1.

In each map shown in Figure 2.1 concept 1 is the subsuming concept and is placed at the top of the hierarchy. Each concept map consists of three basic elements: concepts, linking words describing the relationship between two concepts, and the directional arrow defining the hierarchical nature of the relationship.

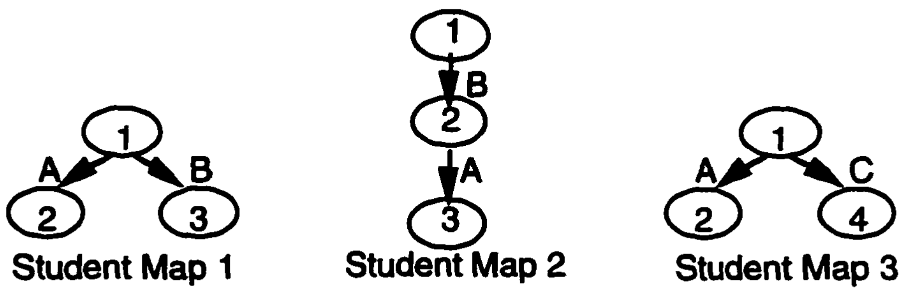

Figure 2.1. Example maps showing concepts as numbers, links as letters and arrows for direction of links, reflecting unique schemas.

To create a hierarchical concept map according to Novak's standards, the student has first to order the concepts, deciding which are the most subsuming concepts, then add subordinate concepts and examples with the appropriate links. Examples are considered to be the terminators on branches. Structural features of the concept map reflect the level of student understanding: web-like branching, deep levels of hierarchy, good choice of propositions linking the concepts, and significant crosslinking between hierarchical levels are interpreted to indicate more complex conceptual schema and mental processes as described in Ausubel's Theory of Learning. The deep processing required for the construction of hierarchical concept maps requires time for training and map development.

Language in Representations of Knowledge Structures

In Ausubel's theory, language plays an important role in concept formation, coding, shaping and acquiring meanings (Novak, 1987). Unlike Piaget's Kantian view that all would eventually arrive at the same cognitive destination but merely at different rates, Ausubel's learner develops shared conceptual meanings, but a unique conceptual schema (Novak, 1987). These unique connections between concepts and the interrelationships of connected knowledge are important features of knowledge frameworks. To understand what it is that students really know, the focus must be on how learners' propositions are woven into the complex web of relationships (Smith, diSessa, & Roschelle, 1993; Clement, Brown, & Zeitsman, 1989). If individual propositions are less important than the framework uniting those ideas, then analysis that captures characteristics of that framework and preserves the context of the ideas may be useful in evaluating what the student knows and in grounding further instruction.

The use of constrained concepts in mapping tasks.

Traditional concept maps and semantic networks are typically freely-drawn. When free choice is allowed for the representation of a domain in a concept map, infinite variations seem possible, reflecting the unique mental schema of each learner. Novak (1984) suggested that as an alternative to free mapping of concepts, students can be asked to map a set of concepts provided. A study by Champagne, Kloppfer, Desena and Squires (1981) used a method called Concept Structure Analysis Technique (ConSAT) in which students constructed concept maps by arranging a set of cards on which concepts had been printed. Students then explained the relationships between the concepts while the researcher extracted linking words from the interviews. The study revealed similarities between the maps: given a set of concepts, concept maps could be consistent, with words of similar meaning used to explain relationships. Further support for common language is found in the longitudinal study of Novak and Musonda (1991) who observed that, although different words are used, similar statements may be found among students' freely drawn concept maps of a domain. When the concepts are constrained, one may expect to recognize some similarity between the maps. The topography of the maps may appear to be different, but some patterns should be observed in the connections formed.

Further support for the use of lists of concepts may be gathered from other models developed by cognitive psychologists to represent student's knowledge structures. One of simplest techniques to design and implement is ordered recall, sometimes referred to as the ordered tree. The primary advantages of the ordered tree are that no prior instruction in the technique is required, it is easy to design and fast to administer, and the assessment can be computerized for total objectivity. The ordered tree is classified as a distance measure that compares similarity of pairs of terms and results in a matrix of similarity ratings for all pairs. The ordered tree technique falls under the category of free recall tests, but as such it has limited applicability. This seldom used technique was given a new twist by Naveh-Benjamin, McKeachie, Lin and Tucker (1986). Their method used a four page booklet with sixteen concepts printed on each page in different four by four matrices. By providing the lists of terms, students were tested on their cognitive structure rather than on their memory. Students had the task of arranging the terms in vertical order based on relatedness. Later a computer algorithm was applied to extract the numerical distance matrix from the four representations. The ordered tree that resulted from the combined matrices shows the amount of organization of the cognitive structure. Hierarchical depth can be inferred from the tree structure, and clustering of the terms is shown in the pattern.

Gussarsky and Gorodetsky (1988) applied the ordered tree technique to the pre- and post-instruction study of student understanding of chemical equilibrium concepts.

The research produced averaged concept maps based on matrices of paired concepts for two groups of students; a significant difference was found between pre- and post-instruction concept pairs. A major disadvantage of the ordered tree method, when compared to traditional concept mapping, is that there is no indication of the relationships between terms, and the framework used to categorize concepts is not always readily apparent. The advantages that accrue from the use of provided concepts are the freeing of working memory for cognitive tasks, the ease of data collection, the possibility of direct comparisons of map structures, and the ability to create an average or composite of group data.

The use of constrained linking phrases in mapping tasks.

The choice of linking words adds an important dimension to the assessment of understanding. Although connections between concepts indicate a relationship, the nature of the relationship is ambiguous. The linking words define the relationship and provide an indication of the student's depth of understanding. If a learner does not think deeply about the relationships between concepts they are likely to choose weak linking words which do not adequately describe their understanding nor indicate a significant relationship.

Despite the variation in linking phrases freely selected by students to portray the relationship between two given concepts, linguists seem to agree that there is a limited range of generic phrases that may be used to describe relationships between concepts in a domain (Spradley, 1979). Many of the freely selected links may be identified as synonyms, and although there are slight variations in meaning, generic terms may be applied. When freely selecting linking phrases, a student may limit selection to simple propositions, and overlook more complex relationships. Students of lower ability are most likely to benefit from the scaffolding provided by use of generic links. Hoever, even when the set of linking phrases is provided, learners at the lower end of the knowledge spectrum may be expected to choose a simple linking phrase to describe a relation between concepts while students at higher levels of understanding choose a more powerful and complex linking phrase that conveys deeper understanding of the relationship.

Further support for the use of language-constrained mapping is found in methods for constructing semantic networks to represent structural knowledge. Dansereau researched the use of generic, categorical linking phrases for semantic networks. Early research by Dansereau and Holley (described in Jonassen, Beissner, & Yacci, 1993) indicated that although six categorical links are limiting, a more complicated system using thirteen links proved too difficult for students to remember and apply. Dansereau's work with semantic maps allows students to freely select concepts but restricts linking terms to categorical relationships such as part, type, analogy, leads to, characteristic. Completed networks, like concept maps, are linked by labeled lines that categorize each relationship.

Language-constrained concept mapping.

Prior research indicates that when students select their own concepts and linking words, the maps are idiosyncratic, comprised of varying numbers of concepts, different concepts, and different linking expressions. Still, is uniqueness possible when all students use the same sets of concepts and linking words? Regis and Albertazzi (1996) gave chemistry students two guided choice concept mapping tasks in which they selected ten out of twenty terms to develop a concept map. Despite the fact that the language in these concept maps was constrained, the researchers comment "we soon had to recognize that students' CMs are highly idiosyncratic representations of domain-specific knowledge, and the interindividual differences displayed among them were far more striking than the similarities" (Regis & Albertazzi, p. 1088). Despite the observation that the resulting concept maps are idiosyncratic, language-constraint provides all students with the same set of construction materials and makes possible the direct comparison of the structures students create.

Benefits of language-constraints in concept mapping.

There are several advantages of using language constraints for mapping tasks. An advantage of using categorical links is that students are cued to divergent thinking about the relationship. A richness of conceptual representation can be evoked by these cues. Another benefit from providing a limited but diverse range of link types is that more processing space remains available in working memory. The cognitive load is lessened since the student does not need to spend time generating the list of concepts and linking words. The studies presented in this section have set the stage for language-constrained concept mapping.

Limitations of language-constraints in concept mapping.

There are at least three disadvantages of using language constraints for concept mapping. First, limiting the concepts may prevent the student from expressing aspects of knowledge about the topic that may be significant to appraising her understanding. Individual free-mapping tasks are characterized by a broad selection of concepts that reflect the student's unique perspective. The range and depth of concepts included in a freely constructed concept map are among the indicators of the level of student understanding of the topic. The second disadvantage accrues to provided linking words. Fisher (1990) observed that although there may be agreement in the concepts related to a topic, there is not a "shared vocabulary" to describe the relationships between those concepts. Fisher notes that the naming of relations is challenging to the student, but an important and instructive process that clarifies meaning. Provided linking words specific to the subdomain may be different from those that a student would freely select, depending on her depth of understanding of the relation. Although the student recognizes an association between concepts, none of the provided linking words may seem appropriate. Also, the misinterpretation of a provided linking phrase can lead the student to select an inappropriate relation. The third disadvantage is evident in the mapping process. An unmotivated student may connect provided concepts without careful thought about the relationships shown and construct a meaningless web of terms.

Methods of Constructing Concept Maps

Traditional Concept Mapping

Traditionally, concept maps are produced with pencil and paper. The task of drawing the concept maps can take a long time, and the maps evolve as concepts change and students perceive new relationships and improve their maps. Novak recommends that students redraw the original map to reorganize for clarity and meaning as well as for neatness. (Novak and Gowin, 1984). Student drawn pre- and post-instruction maps show the integration of new knowledge and changes in conceptual schema.

Edwards and Fraser (1983) found that student-produced concept maps are a valid and valuable means of representing what a student knows. Novak and Gowin (1984) stress that the more actively involved the student is in constructing meaning, the more likely they are to achieve meaningful, long term learning. Post-tests administered several weeks or months following concept mapping experiences confirm the long term effects of constructing meaning through concept mapping (Heinze-Fry & Novak, 1990). Learner constructed concept maps are strongly generative, foster understanding of meaning, and are applicable to any hierarchical knowledge structures. However valuable an exercise, the re-drawing and restructuring of complex maps is tedious and time-consuming.

Much research has been done to efficiently teach students to draw concept maps, and it may be possible to teach concept mapping in an hour or two (Markham, Mintzes, & Jones, 1994), although Regis and Albertazzi (1996) report that four to six class periods of intensive concept mapping instruction are required for mastery of the skill. Still, concept mapping has the advantage of relative simplicity that does not restrict its application to advanced students. Even young primary school students have been found to be capable of constructing and explaining meaningful concept maps (Novak & Gowin, 1984, Stice & Alvarez, 1986).

An alternative to student creation of the concept map is the construction by the interviewer of the concept map based on the collective statements made by the student. The interviewer uses interview tapes to reflect on and revise the draft of the concept map. The judgment of the interviewer introduces another factor despite the intention to remain objective. The construct validity of this concept mapping technique has been established repeatedly as different trained interviewers could be shown to map highly similar concept maps from taped transcripts of the same student interviews. As a consequence of following carefully prescribed methods, interrater reliability of this technique is very high. The benefits that accrue from intense learner involvement in the mapping process are lost with this method.

Whether drawn by the student or the interviewer, the traditional concept mapping is a very time-consuming process. Computerized alternatives to the paper and pencil techniques of concept mapping have been developed (Fisher, 1994, 1990; Schvanevelt, 1990; Beyerbach, 1990), and the salient features of these applications can perhaps be further extended and combined with language constraints to develop a more efficient method of constructing representations of knowledge structures. Schvanevelt (1990) and Fisher (1990) have made notable contributions to the computer-based analysis of knowledge structures, and the following section examines some of the features of these software programs.

The Application of Technology to Concept Mapping

Pathfinder analysis.

Pathfinder Network Analysis (Schvaneveldt, 1990) is a distance measure representing structural knowledge based on related terms. Students are given all possible pairs of terms in random order and are asked to rate them on a scale of perhaps four or ten. An advantage of Pathfinder Analysis is that the entire procedure can be done at the computer, from the random selection of rating pairs to the final statistical correlations. Research reveals that the larger sets of about thirty concepts have more stability and better predictive validity, but the disadvantage of the method is immediately apparent: there are (n(n-1)/2 pairwise ratings for n concepts which must be rated, and that becomes an ominous task for larger conceptual networks. At the beginning, the student may be shown highly related and unrelated pairs as anchors for the comparisons. Very high and very low ratings are to be reserved for certainty; the student is advised to use middle ratings when unsure of relatedness. During the task the student is not given a view of the domain or access to previous responses, but is expected to quickly and spontaneously rate each pair presented. Although consistency and reproducibility would seem doubtful, maps are surprisingly reliable for repeated tests of the same learner even though individual pair ratings are likely to differ within a point or two in a re-test.

Based on the pair-wise ratings, distances are averaged for each pair of concepts, and a proximity matrix is constructed from which calculations determine whether a weighted link is placed between the concepts in the map. The graphic representation consists of linked nodes whose physical distances are unrelated to the weighted distance measures and which appear in no hierarchical order. A hierarchical structure for the Pathfinder network can be forced by manually clicking and dragging the nodes on the computer screen to new positions until a satisfactory structure emerges. Weighted distances can be selectively represented. Showing only those links above a specified level visualizes the strength of the links between concepts.

One advantage of Pathfinder Analysis is that a semantic network is derived directly and objectively from the student ratings. A disadvantage is that the links are not labeled, leaving the relationship between the concepts ambiguous. Still, the procedure requires little training, the ratings can usually be completed within an hour, and the pairwise links are clearly identified in a graphic representation.

SemNet.

SemNet is another application used to construct complex semantic networks. SemNet, developed by Kathleen Fisher and colleagues (Fisher, 1994, 1990; Miller, Faletti, Joseph & Fisher (1991), is a fully developed computer tool for the construction of semantic maps. Two features of SemNet are departures from Novak's traditional concept maps. First, the maps created in SemNet do not necessarily conform to the top-down organization of hierarchical structures. Directional labeled links that may radiate in all directions from central concepts are essential components of the constructs. Second, Fisher emphasizes the importance of bi-directionality of links, and requires carefully selected reciprocal propositional labels which may be used from the available list or supplied by the student. Symmetric links such as "binds with" are admissible but rarely acceptable.

A distinct and powerful advantage of SemNet over paper and pencil mapping is the ability to link graphics and sound as well as text and other symbols in a multimedia creation. The software does the drawing, and the user is free to focus on the conceptual relationships. Another advantage of SemNet is the ability to store the map and to integrate thousands of concepts into a framework that may scroll over several pages, creating hyperlinks between concepts. A disadvantage is that the user is tied to the technology and loses some flexibility to work on the map at any time or place. Another disadvantage is that the large semantic network makes it difficult to get an overview of the organization of the ideas presented.

SemNet, designed by Fisher and colleagues primarily as a learning tool, is comparatively easy to learn. Fisher reports that the program has been used effectively by seventh grade students (Fisher, 1990), and she reports evidence of its effectiveness with nine introductory biology college students who used SemNet over a period of six weeks. The students showed steady increase in test performance while using SemNet, whereas previous research showed no such increase when students generated pencil and paper concept maps for similar time periods. Time on task for the two studies was not reported, and the novelty of the SemNet exercise may have contributed to the extrinsic motivation of the students. Furthermore, the ease of manipulating virtual elements of a map may be preferred by students who are already accustomed to working in that medium.

Benefits of applying technology to concept mapping.

Several benefits accrue from the application of technology to the construction and analysis of knowledge structures. Maps constructed on the computer can be saved for later use. A student may wish to continue work on an earlier map, adding concepts and modifying as learning broadens and deepens. Changes may be made without the need to completely re-draw a map to obtain a good copy of the desired configuration.

Although ease of generating the concept map is important, the ability of the technology to rapidly transform the concept map into coded data for evaluation is a major contribution. Graph theory (Stefik, 1992) proves that elements may be moved topologically, but if the nodes or concepts remain connected in the same way, the resulting structures are equivalent. A coded list or matrix that preserves these connections preserves the integrity of each concept map while removing the topological factor that makes the visual comparison of two concept maps challenging. Once the map is reduced to a simple code of relations shown, evaluation can be expedited by using computer software. Applied to the construction of concept maps, technology efficiently represents the way students see ideas connected and automates the process of collecting the data.

Summary

Concept maps represent the interrelationships within a domain using the structural components of concepts, linking phrases, and directional arrows that organize the hierarchical relationship between ideas. Individual relations are less important than their context, which reveals more accurately what the student knows about the domain.

Language is an integral part of concept mapping, and although traditional concept maps are usually freely-drawn, the use of language-constraints in concept mapping is supported by research such as Regis and Albertazzi (1996), Gussarsky and Gorodetsky (1988), Naveh-Benjamin, McKeachie, Lin and Tucker (1986), and Champagne, Kloppfer, Desena and Squires (1981); Groulx and Dansereau (in Jonassen, Beissner, & Yacci, 1993), and Spradley (1979). Freely-drawn maps are expected to be unique, but research by Regis and Albertazzi (1996) reports that the idiosyncrasy of concept maps is more striking than the similarities between the concept maps, even when language-constraints are applied. Constrained language has several advantages in concept mapping such as reduced load on working memory and cueing to deeper thinking about the relations between concepts. Further, language constraints resolve the problem of comparing the disparate content of concept maps.

Concept maps are traditionally rendered either by an interviewer or by the student using pencil and paper. Although student drawn maps are strongly generative and result in long-term learning, hand-drawing and revision is a very time-consuming process. Two models of technologically assisted knowledge probes that expedite the construction process were presented. Pathfinder networks use constrained lists of concepts but do not provide a visualization of the relationships during the rating process. SemNet is a program used to construct computer-based semantic maps. Students use SemNet to arrange freely-selected concepts and relations on the computer as they would on paper. The SemNet model could be extended to allow students to construct a map by moving and connecting provided concepts and linking phrases on the computer. Students can easily change relationships without the tedium of re-drawing. Unlike SemNet which is designed primarily as an individual study and organizational tool for creating comprehensive semantic networks, The Computer-assisted Concept Mapper limits the scope and depth of the student concept map in order to examine student understanding of interrelationships between a specific set of concepts. CCM also differs from SemNet in that CCM does not include attached graphics or sound to depict concepts or enrich meaning, relations between concepts in CCM are not required to be bi-directional, and in CCM students are given all concepts and linking words.

Language-constrained concept mapping plays the middle-ground between traditional concept mapping and Pathfinder analysis. Students can link ideas that they associate but are not required to conform the map to a hierarchical schema. Less time may be required for the training and map construction. Language-constrained computer-assisted concept mapping using The Computer-assisted Concept Mapper would provide automated and efficient data collection with a common data set that allows for direct comparisons of concept maps.

Another challenge is to find an efficient method of evaluating these language-constrained computer-assisted concept maps for large numbers of students. Part Three reviews support for the validity of concept mapping as a representation of domain knowledge. Traditional approaches to the evaluation of concept maps are reviewed. Part Three then presents a protocol for the comparison of language-constrained concept maps and an algorithm derived from Pathfinder analysis for the comparison of concept maps. A measure of the structural complexity of concept maps finds a basis in graph theory.

Part 3: The Evaluation of Concept Maps

The Validity and Reliability of Concept Mapping

The Validity of Concept Mapping

Concept maps derive construct validity from various sources: their foundation in Ausubel's Theory of Learning, the procedures used to select the domain and concepts, the validity of the clinical interview methods used to derive student maps, and by procedures used to score and analyze the maps. Numerous research studies have supported the validity of concept mapping as a teaching and learning tool. Concept maps have broad application and have proved to be useful for helping students "learn how to learn", and evaluating students' understanding of interconnected knowledge and conceptual change (Donovan, 1983; Pankratius, 1987; Heinze-Fry & Novak, 1990; Novak, J.D., 1990; Starr & Krajcik, 1990; Wallace & Mintzes, 1990; Novak & Musonda, 1991; Novak & Wandersee, 1994; Pendley & Novak, 1994).

One difficulty in validating the effects of concept mapping has been the selection of tools for parallel but broader assessment of the knowledge. Novak, Gowin, and Johansen (1983) compared concept mapping scores, course grades, and scholastic aptitude tests, and found low correlations between them. One interpretation of their data is that concept mapping does not correlate with other tests and measures because traditional measures such as multiple choice tests often do not discriminate well between meaningful and rote knowledge, but more holistic evaluations of student performance such as course grade are found to correlate with concept mapping scores.

Songer and Mintzes (1994) developed a test instrument of open-ended free-response questions based on collated propositions culled from student concept maps. Pankratius and Keith (1987) used multiple choice higher order questions of application, analysis, synthesis as correlates and found that students in the treatment groups more often answered correctly, implying correct conceptual organization. Concept mapping scores generally correlate well with problem solving tests and other questions that measure usable applied knowledge.

White and Gunstone (1992) argue that when the goal of learning is understanding of the interconnectedness of knowledge, concept mapping provides a valid assessment method. Standardized test measures have not been found to afford the concurrent or predictive validity of concept maps; typical multiple choice tests focus on simple isolated facts and cannot convey a more global understanding of the topic or the interrelationships among the propositions that are visualized by the concept map. Their research supports the validity and reliability of concept maps as a measure of students' functional knowledge, and shows that concept maps generally correlate well with problem-solving that measures usable knowledge. Their research reaffirms that concept maps usually compare poorly with typical standardized tests which may test rote-learning.

The Reliability of Concept Mapping

Research supports the reliability of student constructed concept mapping. The reliability of map scores for concept maps produced by the interview method and based on a student's collective transcript statements was enhanced by the thorough training of the assistants responsible for drawing the maps and scoring them. High interrater correlations were found in research studies (Novak & Mussonda. 1991; Edwards & Fraser, 1983). Indicative of its ability to report the same situation the same way, students given a set of concepts and linking words produce similar representations when no intervening instruction has occurred. For example, a study involving ConSAT, which involves a task similar to concept mapping using a set of related science concepts found that the task repeated over time produced essentially the same representations for most students (Champagne, Kloppfer, Desena & Squires, 1981). Shavelson (1993) notes however, that in general practice the numerous variations in concept mapping techniques and scoring methods may compromise reliability and limit the consistent application of concept mapping for assessment purposes.

Another aspect that impacts the validity and reliability of concept mapping is that traditional concept mapping studies have characteristically used small numbers of participants, especially when scoring of the concept maps and or construction of maps from interviews are required by the study. Horton's (1993) meta-analysis of nineteen studies on the use concept mapping as an instructional and learning tool in science education showed a range of n values. In general, larger n values were associated with the use of other test instruments to evaluate the effectiveness of concept mapping. Typically smaller n values were associated with studies that actually scored or compared concept maps. The traditional process of evaluating concept maps is very labor intensive and requires a cadre of skilled reviewers if large numbers of maps are included in the study.

Traditional Methods of Evaluating Concept Maps

Scoring Rubrics

Novak and Gowin (1984) moved concept mapping beyond use as a learning or instructional tool into the arena of assessment when they proposed a quantitative scoring rubric linked to content structure of concept maps. Quantified map scores enable statistical comparison of instructional treatments and raise concept mapping to the level of a diagnostic tool to monitor, quantify, evaluate conceptual change, and prescribe further instruction (Schreiber & Abegg, 1991). The scoring rubric suggests one point for each valid relation, five points for each level of hierarchy, ten points for each significant cross link, one point for each valid example or instance (Novak & Gowin, 1984). The lowest point assignments indicate easily achieved subsumed cognitive links, and more points are assigned to relations representing integrative reconciliation. Although a total map score embeds certain critical map characteristics, a similarity between two map scores does not guarantee a similarity between relationships within the concept maps. The scoring method attempts to convey a global evaluation of the map; however, local information about the conceptual schema is lost in the composite score.

Schreiber and Abegg (1991) propose a modified, although no less tedious, method of scoring student maps. They quantify salient characteristics of concepts maps while attempting to eliminate the bias and arbitrariness associated with qualitative scoring methods. Specifically, they evaluate three aspects, the amount of information the student possesses, the student's reasoning ability, and misconceptions. A category score for propositional validity represents student reasoning ability measured by the ratio of valid connecting lines to the total number of connecting lines drawn on the concept map. Hierarchical structure reflects the amount of information since the well versed student is expected to have more concepts at each level in the hierarchy than one who knows little about the concepts. Misconceptions are most often associated with maps that have few strands of relations. In this study by Schreiber and Abegg, the maps were compared with a criterion map developed by three experts, and map constructs were identified such as total number of vocabulary terms, number of hierarchical levels, number of connecting lines drawn, number of connecting lines validly labeled, number of strands recognized, and number of cross-links between strands. Ratios were calculated to tabulate student proficiencies and skill, and an overall map score determined mathematically. Schrieber and Abegg concluded that their scoring protocol can successfully diagnose the level of student understanding.

Markham, Mintzes, and Jones (1994) utilize the traditional scoring method but retain the five separate factors instead of summing them to obtain a map score. Each factor relates to a cognitive skill: the number of concepts indicates the scope of knowledge; branching reflects progressive differentiation; hierarchies represent knowledge subsumption; crosslinks, the extent of knowledge integration; and examples indicate the specificity of knowledge. Some local information about the concept map is preserved in the separate factors, however, similar scores do not imply similar maps.

Scoring by any of these rubrics can be very time-consuming, and when large numbers of maps are scored by teams of evaluators, methods must be introduced to assure the consistency of the scoring. Increased reliability and objectivity results if each map is scored by more than one evaluator using a clearly defined method.

Use of Referent Structures in the Evaluation of Concept Maps

When a concept map is scored using the traditional scoring method, the teacher must be familiar with the domain in order to evaluate the correctness of each relation. Much the same as creating a template of correct answers to a test, a referent or criterion map may be used to compare the maps. Sources of referent maps are typically a single expert in the domain, the teacher, or a good student. A composite map of several experts, teachers, or good students may be used as a referent. If a referent is used, criteria are often set to calculate a percentage score for each student. (Novak & Gowin, 1984, p.36).

The use of a referent developed by the instructor is validated by findings in two research studies by Beyerbach (1986). Concept mapping was used to assess progress of student teachers on the premise that concept maps developed by the prospective teachers during a semester education course would become more organized, differentiated and include more concepts over time. Beyerbach reported both qualitative and quantitative analysis of concept maps. The research revealed that over time a shared vocabulary developed between instructor and students. Beyerbach also observed that concept maps generated during the course began to more closely approximate the instructor's map. Although similarity to instructor was found in this study, similarity of student to expert is rarely found, and a referent map designed by experts in the field is not expected to be congruent to student maps. Goldsmith and Johnson (Schvanevelt, 1990, chap. 17) note that for novice learners, the classroom teacher is a good model, and top students might also be used for comparison. Goldsmith and Johnson further remark that a comparison between students was found to discriminate good from poor students.

The method of comparison developed by Beyerbach and Smith (1986) looks at global characteristics as well as specific links between concepts and is based on the instructor's map as referent. Their scoring protocol expands on Novak's scoring method by including the item or number of accepted relations score (degree of differentiation), item stream score (number of distinct super ordinate concepts), levels of hierarchy score (degree of hierarchical organization), similarity to group score (related to group consensus or frequency of entry), similarity to instructor score (identical entries), and item stream similarity to instructor score (streams identical to instructor's). Their findings show that more advanced students are more likely to adopt the instructor's conceptual framework than are less advanced students. Students who had prior coursework showed gains in the similarity to instructor score while students with no prior coursework broadened their repertoire of concepts and showed an increased item score. Similarity to group scores increased from pre to post mapping tasks, which indicates that as students gain expertise their maps become more similar. Goldsmith and Johnson (Schvanevelt, 1990) also found increasing similarity between students as they progressed in a course. This finding may be most significant to this dissertation. Despite the fact that student concept maps remain unique, personalized schema, this finding suggests that it may be possible to compare student maps with one another to discover developing patterns of understanding.

The composite map score attempts to convey a global evaluation of the concept map, but rather than focusing on individual map scores, there may be much to be learned about school learning from the direct comparison of large numbers of concept maps.

Such a comparison presents a formidable task, given present methods of evaluation. One way that researchers represent the understandings common to groups of students is to dismantle student concept maps and frameworks into lists of accepted propositions along with the percentage of students representing each proposition in a concept map. Although this may be informative, technology may permit more powerful comparisons that represent the interrelations and context of the propositions.

The Application of Technology to the Evaluation of Concept Maps

SemNet: Evaluation of Structural Characteristics of Computer-based Concept Maps

Fisher (1990) views student maps as unique, individual representations of knowledge. The sprawling nature of an "all inclusive" SemNet map makes it challenging to assess, but the teacher can acquire a global view by traversing on "auto-pilot" only well developed links to get an overview of the quality of the SemNet map. SemNet also provides a built-in measure for quantitative overview which presents the most developed concepts or concepts having the most instances, a factor that relates to the scope of knowledge. The embeddedness of concepts, defined by the count of links to a concept from two concepts away, is a measure of branching characteristics and differentiation; and a count of the most used relations provides a measure of the depth of thinking about the concept. Several graphical displays of the inter-relatedness of concepts are also available in SemNet to provide a visualization of the spiraling knowledge core, showing the hot spots or highly embedded concepts in the map. It is possible to extract hierarchical representations. These various representations can provide a condensed and holistic view of map characteristics. Statistical analysis and comparisons of SemNet maps are accomplished using tools built into SemNet which convert and export quantitative data for each map, but the procedures are still complex and time consuming when analyzing and assessing maps for large numbers of students. The SemNet approach shows that information about the scope and depth of knowledge represented in a semantic map may be evaluated with total objectivity on the basis of structural features that the technology can easily assess without comparison to referent structures or judgment as to propositional validity of individual relations.

Developing a Protocol to Analyze Levels of Understanding

Acceptance of all relations in student concept maps and comparison of all maps to one another opens a different approach to concept map evaluation. The work of Gussarsky and Gorodetsky (1988) using word associations to get at student understanding suggests a strategy for the comparison of concept maps that relates to their structural elements. At the most basic level of constructing a concept map, the student forms propositions, joining two concepts with a linking phrase. The sequence of mental tasks required while forming each relation would seem to provide different information about the cognitive structure represented. Gussarsky and Gorodetsky note that forming a link between concepts without specifying the nature of the association demands little analytical thinking. Paired concepts measure a static aspect of understanding and can imply no more than a crude grasp of a relationship. The degree of relatedness or nature of the association is not demanded by the simple act of pairing concepts. The selection of the linking words describes the relationship between the concepts, determines the hierarchy of the relationship, and informs the directional arrow of the link. Learners with only a rudimentary understanding of the domain may recognize that certain concepts are related, but may choose inappropriate or weak linking words or confuse directionality of the linking proposition. The basic link between concepts, the linking words, and the directionality of the link between concepts each contributes increasing depth of understanding to the relation.

Comparison of the elements of concept maps provides information about the student's level of understanding. The evaluation of the lowest level of understanding considers only which concepts are used, and at the next level, which concepts are linked together. Both of these extractions reduce the concept map to a static representation. Delving deeper, the use of appropriate linking words indicates the level of analytical understanding of the relationship between concepts. When the linking phrase and the directionality of the link between the concepts are correct, the student demonstrates a dynamic understanding of the relationship and the hierarchical structure. A dynamic level of understanding characterizes meaningful useful knowledge (Gussarsky & Gorodetsky, 1988).

The focus on the structural components of concept maps is further supported when elements of graph theory (Stefik, 1992) are applied to the analysis and comparison of concept maps, helping to define equivalence between representations. Graphs are composed of nodes or points connected by arcs; nodes are analogous to concepts and arcs may represent directional links between concepts. Distance and topological arrangements are irrelevant in graph theory. Two graphs are considered to be identical or isomorphic when the same nodes are connected and the direction of the arcs is preserved; two concept maps would be identical if the same concepts are connected using the same linking phrase and the direction of the relation is the same. The protocol for the evaluation of concept maps prescribes the comparison of their structural elements. An algorithm for the comparisons may be derived from the analysis of Pathfinder networks.

Pathfinder Analysis: An Algorithm for the Comparison of Similar Structures

Research by Goldsmith, Johnson, and Acton (1991) evaluated Pathfinder analysis and multidimensional scaling and concluded that Pathfinder analysis was better at predicting similarity between knowledge structures and performance in the domain than either raw proximity data or multidimensional scaling. Pathfinder focuses on individual local connections, but the proximity matrix transforms to a graphic network showing the strongest links in a web of concepts. The common data set and the matrix format invites comparisons between networks. The intriguing idea is that the reverse process should also be possible: that common data set of language-constrained concept maps could be converted from the graphic representation to a matrix format for between-map comparisons.

Perhaps even more significant to this dissertation is the algorithm developed for the comparison of Pathfinder networks. Pathfinder analysis uses a global variable called the closeness coefficient, C, that derives a similarity ratio from two proximity matrices by computing the union and the intersection of sets of connected concepts in the two Pathfinder networks, focusing on the neighborhood surrounding each concept in the network. The variable C was found to reflect global relationships of the matrix and to have predictive value. Students grouped by ability were found to have significantly different average C values. This study also supported the hypothesis that high achieving students would have similar cognitive representations as measured by C, and that low achieving students would have disparate representations. Pathfinder analysis offers a significant contribution to analysis of networks with the identification of maps sharing global similarity as measured by the closeness coefficient C.

The algorithm can be applied to language-constrained concept maps. Similarities between concept maps in concepts used, concepts connected, concepts and linking phrases, and relations would provide analysis of similarities in depth of understanding. These similarity measures may be followed by other statistical methods such as cluster analysis to identify groups of similar maps, or maps of students who have achieved a similar level of understanding or way of seeing these concepts connected. Global patterns that emerge from maps of students who have similar ability and shared conceptions are more effectively conveyed by graphic representations available through Pathfinder than by purely quantitative measures, lists, and graphs.

Composite Concept Maps as an Evaluative Tool

Composite maps generated from matrix data are expected to show differences between groups at different levels of understanding. A distinct advantage of the computer-based method is that the comparison using sophisticated statistical analysis, not otherwise available to the researcher, is facilitated for large numbers of subjects. When small numbers of subjects are studied, idiosyncrasies may overwhelm the more subtle similarities. Fine-grained differences in levels of understanding within a domain may emerge when large numbers of subjects are compared. Composite maps that show all student connections between concepts have been used by Songer and Mintzes (1994) to anticipate the many common errors that can present impediments to learning about a topic.

Characteristic differences between novice and expert knowledge should be useful in identifying levels of learning. Graph theory (Stefik, 1992) may also contribute to the assessment of structural complexity of concept maps. Structural complexity is a unit rating assigned to the graph where 1 represents a simple linear graph structure, and n represents a graph structure of n nodes completely connected, each node to every other node. Although this would be impractical to measure otherwise, technology makes possible the calculation of the "width" or structural complexity of a concept map. The width of most concept maps, however, may not vary sufficiently to use this measurement as a discriminant. Cyclic arrangements of nodes are also indicative of graph complexity. Since complexity is expected to increase with understanding, such objective quantitative measures of the knowledge structure represented may help to order the composite concept maps by levels of understanding. A progression in learning may emerge from the comparison of the composite concept maps.

Summary

In summary, concept mapping has been shown to be a valid and reliable tool for learning, instruction, and assessment of understanding. Concept mapping has been validated by correlates such as course grade or assessments requiring application of knowledge. Although reliability or consistency has been reported for studies over time, variations in techniques and scoring methods may compromise the reliability of concept mapping as an assessment tool.

Quantitative scoring rubrics foster the use of concept mapping as an assessment tool. Traditional scoring of concept maps focuses on the individual's map score; however, similar composite map scores do not imply similarities in the map structures. Referents may be used to score maps. Student maps are found to become more similar to the instructor's referent map and more similar to maps of peers as a course progresses and student expertise increases in a domain. This finding suggests that the comparison of maps to those of other students may identify different levels in understanding.

Gussarsky and Gorodetsky suggest that depth of knowledge is reflected in the elements of concept maps: concepts, links, and directionality as learning develops from static to dynamic and useful knowledge. Based on this observation and the support of graph theory, a protocol that compares the elements of concept maps may identify similar maps and provide insight into students' levels of understanding.

An algorithm for the comparison of concept maps is found in the closeness coefficient C used by Pathfinder analysis to compare similarities between networks. Pathfinder research suggests that a computerized analysis of concept maps is possible when language-constraints are applied, and can yield valid results. Because concept maps have more complex structural components than Pathfinder networks, the comparison of similarities may be layered to show levels of similarity between concepts, linking phrases, and directionality of the relation that translate to levels of deeper understanding.

Similarities between maps may be calculated to identify groups of similar maps. Graph theory contributes to the evaluation of the structural complexity of concept maps to determine levels of understanding and a progression of learning.

Summary

Concept mapping probes student understanding and mirrors the cognitive processes of hierarchical structuring, integrative reconciliation, subsumption, and progressive differentiation of concepts. Levels of proficiency in domain knowledge may be evident when concept maps are compared. Research shows that experts and novices may use different organizational frameworks, and novices may not use any specific framework. The scope and embeddedness of concepts also differs when concept maps of novices and proficient learners are compared. The connections formed by experts are parsimonious while some connections formed by novices are redundant and contribute little to an understanding of the domain.

Traditional concept mapping requires considerable time to instruct the learner in mapping strategies and for the learner to become comfortable with the mapping process. When changes are made to the map, the time needed to redraw and re-structure the map take valuable learning time. Whether constructed by the interviewer or the learner, pencil and paper concept maps take considerable time to produce. Computer-assisted mapping programs such as SemNet provide alternatives to hand-drawn maps.

Precedent has been set for the use of language-constraints in assessment of structural knowledge. The efficiency of the mapping process may be improved by combining the on-screen mapping process of SemNet with language-constraints. Computer-assisted Concept Mapping that is the subject of this dissertation differs from other mapping tools in that it limits the concepts and linking words used in the mapping task to examine understanding of interrelationships between a relatively few specific concepts. In contrast, SemNet allows the student to build very large, comprehensive semantic maps using hundreds of concepts and relations of their own choosing to fully represent their knowledge of the topic. Another important difference between CCM and SemNet is the use of linking words. The relations in SemNet are always bi-directional and the student must define the reciprocal terms for both rays between concepts (Fisher, 1990). Linking words in CCM apply in one direction, although multiple relations between two concepts are possible.

Students can easily construct and change the virtual maps, and data collection becomes become automated and more practical for large-scale assessments of school learning. Additional benefits accrue from the use of constrained language in constructing concept maps: the provided concepts cue the learner and reduce the load on working memory, and linking phrases may actually cue some students to deeper thinking about the relations between concepts. Some disadvantages of language-constrained mapping are that the maps are limited in scope and depth, cannot reveal the student's full understanding of the topic, and may not allow the student to show a unique perspective. Further, the process of freely selecting appropriate terms for concepts and words to clearly define relations between them is in itself a valuable learning experience that is at least partially sacrificed with language-constrained mapping.

The evaluation of concept maps presents another challenge. The quantitative scoring rubric proposed by Novak (1984) moved concept mapping into the assessment arena. Similar map scores should indicate similar levels of complexity and understanding of the domain, but do not imply similar map structures. Researchers have proposed modified scoring rubrics, some maintaining separate category scores to group similar maps. All scoring techniques are very time-consuming to implement, and when analyzing large numbers of maps require high interrater reliability.

Referent maps have been used as scoring criteria, however similar scores do not necessarily indicate that the maps are similar. Proficient students have been shown to produce maps more similar to the instructor's map over time. Proficient students also produce maps more similar to one another while novice maps are divergent. This pattern of convergence as learners become more proficient in the domain suggests that maps could be compared to one another to identify groups of students at different levels of understanding.

A common construction set of The Computer-assisted Concept Mapper allows direct comparisons and opens a new approach to the evaluation of concept maps. CCM seeks to discover commonalities among large numbers of concept maps that show relationships among specific concepts, revealing patterns of connections that may provide insight into student understanding of a topic. Graph theory and Pathfinder analysis suggest that language-constrained concept maps can be reduced to coded lists or matrices that preserve the relations of the map and facilitate the objective comparison of map structures. A protocol for the comparison of concept maps can be based on the structural elements of concept maps that builds layers of similarity that may reveal deepening levels of understanding. This approach offers an alternative to traditional scoring rubrics for individual maps and looks for patterns of understanding of a domain among students who have studied a similar curriculum.

The C-measure of Pathfinder analysis provides a model for the quantitative measure of the similarity between two concept maps. The calculated similarity ratios may be used to cluster similar maps. The generation of Pathfinder networks from related data suggests that matrices of occurrences for the relations in a cluster of maps may be used to generate a composite map for each cluster. A composite map represents the shared understanding of the group of students who have connected ideas in a similar way. A comparison of composite concept maps is expected to reveal different levels of understanding and a progression of learning.

CHAPTER III

METHODOLOGY AND RESULTS

Overview

This dissertation is designed to determine whether a large number of student-constructed language-constrained computer-assisted concept maps can be analyzed using technology to reveal patterns in students' understanding of a domain. Before this dissertation can explore whether this analysis is fruitful, the validity and reliability of the approach must first be established. This research then examines students' language-constrained concept maps, compares them for similarities and differences in content and construction, and clusters the maps on the basis of these features. Finally, map clusters are analyzed for evidence of different levels of understanding, and for signs of progression of learning. In summary, there are two purposes of this research: 1) to demonstrate that computer-assisted concept mapping using constrained concepts and linking words can be used by students to construct valid concept maps that can discriminate students on their knowledge of the domain, and 2) to discover patterns in the continuum of learning that may emerge from comparisons of these concept maps.

The research consists of four studies. The first two studies are the necessary preliminaries to the core of the research. These studies are designed to assess the validity and reliability of language-constrained computer-assisted concept mapping. The first is a validity study in which language-constrained concept maps are constructed by the same students using the computer and using pencil and paper in separate tasks; the second is a reliability study which compares language-constrained computer-assisted concept maps constructed over time by the same students using the same instruction-free concept set.

The third study, which forms the main body of this research, tests the ability of The Computer-assisted Concept Mapper software tool to discriminate for a large number of students on their knowledge of a domain. Students' language-constrained computer-assisted concept maps on a science domain are compared and sorted on the basis of similarities in their representation of the domain. That is, maps that use the same concepts and show those concepts connected in the same way are grouped and analyzed for patterns in the concepts connected and missing concepts.

The fourth study extends the analysis of the clusters of similar concept maps identified in Study 3 and attempts to discover evidence of levels of conceptual understanding of the domain. The composite map of each identified cluster is examined for features such as structural complexity, connectedness of core concepts, and evidence of a unifying framework for the relationships. The composite maps are sorted on the basis of these characteristics to show a pattern of deepening understanding of the domain. The fourth study also examines composite maps for evidence of developing understanding by grade level.

All four studies compare similarities between concept maps. The next section presents the methodology for a comparison of two maps, and explains the algorithm used to quantitatively report those comparisons.

Development of a Methodology for Comparing Concept Maps

Identifying Similarities between Concept Maps

The following methodology identifies similarities in the concept maps. The first two questions are viable when students are not required to use all concepts provided.

1. Is the same number of concepts used in both maps?
2. Are the same concepts used in both maps?
3. Are the same concepts-connected in both maps? More specifically, whether or not the same linking propositions are used and whether or not the directionality of the linkage is the same, do both maps indicate a relationship between the same concepts?
4. Between the concepts, are the same linking propositions used? More specifically, whether or not the directionality of the linkage is the same, do both maps use the same linking proposition for the relation between the paired concepts?
5. For each pair of matching concepts with matching linking propositions, is the directionality of the relation the same in both maps?

These questions, answered in this order of priority, layer the similarity between two maps. The first two questions evaluate the basic elements of the concept maps, indicating the extent of the links, and use of specific concepts as an index to breadth of understanding. The third question reveals the skeleton of the concept maps, asking only whether the concepts are connected to one another in the same way. The fourth question focuses on the agreement of the linking words used to define the relationship between each matching pair of concepts. The fifth question answers to what degree the concepts, links and directionality of relations match. The fifth question, then, provides the most rigorous and dynamic appraisal of the congruence between the maps, while the first through fourth questions allow for differences in linking words and/or directionality of the relation. Each successive level of similarity testing demands greater congruence between the relations in the two maps compared.

Similarity Measures

The computer-based concept map analysis tool uses an algorithm for the comparison of concept maps similar to the C-measure algorithm developed by Goldsmith and Acton (1989) for the comparison of pathfinder semantic networks. The C-measure looks at the neighborhood of each node or concept in the two networks being compared to see whether the same associations are present. The intersection of common associations is divided by the union of unique associations represented for each node in the two networks. The ratio for each node is given equal weight, regardless of the number of associations to other nodes. Links between two nodes are factored into the calculation for each of the nodes. Each node's ratio has a value between 1 and 0, ranging from total correspondence to total dissimilarity for the node. The average similarity ratio for the network is calculated by summing the ratios for the individual nodes and dividing by the total number of nodes. Taken together, the comparisons provide a measure of the global similarity or congruence between any two networks that has proven to be useful in predicting performance in a domain.

The number of nodes and specific nodes in pathfinder analysis are the same for all networks since they are derived from pair-wise ratings of a set of concepts. Concept mapping does not necessitate that students use all of the concepts provided. This research uses the ratio of intersection to union for the comparison of two concept maps that assigns equal value to each link, rather than to each node. The algorithm used in this research considers the concept map as a whole, and each element is factored into the formula just once. The algorithm is applied to the properties of concept maps with increasing requirements for congruence. The SC-measure calculation looks to see if the same concepts are used in the two concept maps. The CC-measure asks whether the same concepts are connected by any link in any direction in the two maps. The SL-measure compares concepts-connected and includes the linking phrase used to express the relationship between them. The SD-measure compares maps on the basis of concepts-connected, linking phrase used, and directionality of the relation, or in other words, compares the two maps for full congruence. One criterion of a successful algorithm for the comparison of two concept maps is that it yields the same results as a visual inspection of the maps being compared. Figure 3.1 shows a rudimentary set of student concept maps that show some similarities and differences in concepts used, linking phrase selected, and direction of the relation.

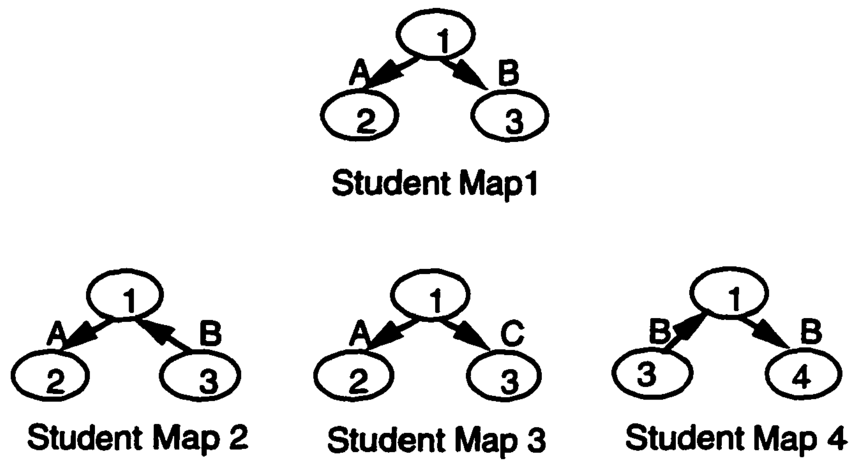

Figure 3.1. Examples of similar student maps representing concepts as numbers and linking phrases as letters.

Calculation of similarity measures.

For each pair of concept maps compared, the similarity measure calculates the ratio of the set of the intersection and the set of the union for the property in question. For example, the SC measure for student map 1 to student map 4 compares whether the two maps have the same concepts. Map 1 has concepts 1, 2, and 3 while map 4 contains concepts 1, 3, and 4. The intersection or common set of concepts consists of concepts 1 and 3, a set of two members. The union is the set of all concepts represented in the two maps: 1, 2, 3, and 4, a set of four members. The SC similarity ratio is 2/4 or 0.5.

The CC measure or similarity ratio for concepts-connected in the two maps compares 1—2, 1—3 in student map 1 with 1—3, 1—4 in student map 4. The intersection is 1—3, a set of one member. The union consists of 1—2, 1—3, and 1—4, a set of three members. The CC similarity ratio for concepts-connected in the two maps is 1/3 or 0.33.

Goldsmith and Johnson (Schvanevelt, 1990, chap. 17) found that comparisons among students could discriminate between good and poor students. Further, Goldsmith and Johnson suggest that finer grain differences among students may be revealed by similarity measures. Cluster analysis based on similarity ratings between all pairs of student maps is used to identify groups of similar student maps. Each cluster of maps is then condensed to a composite concept map that visualizes the relations and characteristics of the cluster. The features of the composite concept maps are then examined for evidence of a progression toward deeper understanding of the domain.

In addition to these similarity measures, student maps may be compared to a referent map of an expert or teacher. Although these comparisons are possible, they are not the focus of this research. Prior research as shown that student maps become increasingly similar to the instructor's map as a course progresses; however, in this study, the researcher is not the classroom teacher for these students. There is little reason to expect strong similarities between student maps and the researcher's map in this study. The purpose of this research is not to identify only accepted relations, or to score an individual map on the basis of similarity to an instructor's map. The purpose of this research is to identify groups student maps that are similar, including commonly held beliefs, alternative conceptions and gaps of understanding that are evident in the context of the interconnections. Table 3.1 lists the similarity ratios for the comparison between the student 1 map and other student maps.

Table 3.1

Comparison of Student 1 to Student 2, Student 3, and Student 4 Concept Maps

Measure	Student 1 Compared to		
	Student 2	Student 3	Student 4
SC-Measure	1.00	1.00	0.50
CC-Measure	1.00	1.00	0.33
SL-Measure	1.00	0.50	0.33
SD-Measure	0.33	0.50	0.00

Scale of Ratios

To reiterate, the ratios may be interpreted as percentages, with 1 equal to 100% correspondence or identity, and 0.50 equal to 50% correspondence between two maps on the selected attribute(s). The "goodness" of the values is relative to the level of attribute(s) measured. In other words, higher values are expected from the comparison of concepts used, even when students were not required to use all concepts. Values will tend to be much lower for concepts-connected since not only must the same concepts be used, but they must be connected in the same way. One set of criteria for the "goodness" of the values cannot be established that applies to all attributes, but when clusters of similar maps are compared, the higher ratios or agreement are always better than the low values.

The "goodness" of the values is also relative to each study. A study with a large selection of concepts and linking phrases will tend toward low ratios of similarity between two maps since the pool or union of unique attributes is likely to be large, and intersection of identical attributes small. A large selection of concepts and linking phrases will tend to produce a greater variety in the ratios. The range is always 0% to 100% or 0 to 1.0.

Composite Maps

The concept maps are dismantled for analysis, but each map can be reconstructed to preserve the context of the relations represented. This research proposes that valuable information about student thinking can be culled from groups of similar concept maps. For each cluster of similar maps a matrix is generated for the number of occurrences for each relation in maps of that cluster. KNOT-Mac accepts matrix input and generates a graphic representation of all relations represented. The relations of greatest interest are those relations that have higher occurrence. The relations that are displayed can be limited to those relations that meet or exceed a defined minimum value. Representations can show layers of relations identified by their percent occurrence or strength.

The composite concept map generated for a population shows the scope of the framework and cohesiveness or fragmentation of knowledge as represented by this concept mapping task. A composite map shows the core of knowledge shared by a group of students and allows for comparison between clusters of maps to search for a continuum of the relationships selected. Alternative conceptions represented by a certain percentage of the students will be apparent in the representation. More fragmentation among connected concepts, simpler structures, and redundancy are expected at the novice end of the spectrum, with a progression toward greater integration of relations as the learner approaches deeper understanding. Most importantly, the relations are viewed in the context of interconnections within the concept map.

Participants

Subjects were selected on the basis that students at different grade levels are expected to show a range of understanding based on school learning within the selected domain. This research recruited four hundred and five subjects from regular sixth, ninth, and twelfth grade classes at two middle schools and one high school in a small upper middle class suburban community in which the student population is approximately 92% Caucasian. The cross-age sampling presumed that students are at various points in expertise, having had different experiences and developed different knowledge within the selected concept domain. Available groups of students at each grade level were not the same size. Students were selected from intact classes and are assumed to be of a range of abilities, predominately average and above average in classroom performance.

Permission of the Superintendent of the local school district was obtained as well as initial approval from the IRB Behavioral Sciences Committee for a study involving human subjects.

Intact classes were sought for participation so that the study would include a broad representation of abilities, and a large number of students of average ability. Therefore all sixth, ninth, and twelfth grade science teachers in the local school district were invited to participate in the study. Four sixth grade science teachers at the two middle schools, one ninth grade geology teacher, and both twelfth grade physics teachers volunteered their classes for the study. A consent form was sent home with each student in these seven classes so that student and parent could decide whether the student should participate. A brief description of the purpose of the study and the treatment of students was included on the consent form (see Appendix A for sample consent form.). Students returned the signed forms to the classroom teacher who sorted and recorded their responses. The researcher collected the forms from each teacher.

Treatment in Accordance with Ethical Standards

For each intact class, the students were separated into two groups. While one group led by the researcher worked on the concept mapping task, the non-participating students worked with their regular teacher on classroom activities in another classroom. Participants did not record actual student names or identification for the concept map produced. Each student was assigned an identification label encoding grade level, class, school, and gender of the student along with a number in the sequence. For example, sl2f340 represents a sixth grade student in L's second hour class. The student is female; number 340 in sequence. Fewer descriptors would have been adequate to the study since the classes at each grade level were expected in this case to be heterogeneous groupings.

Research Setting

The research was conducted in one school district with a total student population of about 4200 students. The school district consists of five elementary schools, two middle schools, and one high school situated within a three mile radius. The community has a traditional small town core surrounded by a suburban upper middle class community. The school district is recognized for the outstanding educational achievements of its students. The teaching staff is dedicated and talented; several of the middle school science teachers have received the highest state and national honors for excellence in teaching.

The methodology for each of the four studies will be described in following sections.

Study 1: A Comparison of Paper and Pencil and Computer-assisted Language-Constrained Concept Maps

Overview

Validity measures the ability to achieve the same results by different methods. This study questions whether the use of language-constrained computer-assisted concept mapping is a valid method for assessing students' structural knowledge. The purpose of this study is to show that the method of constructing concept maps does not affect the task, or specifically, that the computer-based tool does not interfere with the concept mapping task. If the computer can be used to produce language-constrained concept maps that are similar to language-constrained pencil and paper maps, this study may conclude that CCM is a valid means of assessing student knowledge. This first study, a test of the validity of the tool, is a two-pronged design to compare two types of language-constrained concept maps, one drawn with traditional pencil and paper, and the other constructed with The Computer-assisted Concept Mapper software, CCM.

Participants

Four students from each group of volunteers at grade levels six, nine, and twelve, a total of twelve students, were selected to participate in the study of the comparison of pencil and paper and computer-based language-constrained concept maps. These students were identified by their teachers as being average or above average in classroom performance. The gender distribution was uneven with nine girls and three boys taking part in this portion of the study.

Concept Selection

An instruction free domain related to common food experience was selected to ensure that intervening instruction would have no effect on the consistency of the concept maps generated by different methods by students at different grade levels. All students who participated in the study were familiar with pizza meals. A concept map was constructed by the researcher to describe the make-up of a pizza and the accompaniments for a pizza meal. Twenty concepts were chosen to include several toppings not necessarily used together on a pizza, characteristics of the crust, and other foods and utensils that might be associated with a pizza lunch such as a salad, breadsticks, beverage and straw. Four generic linking phrases, "is a part of", "is a characteristic of", "is used for", and "is a kind of" that describe the relationships between these concepts were considered sufficient choices for the construction of this concept map.

The concepts were not necessarily hierarchically related. Since all concepts need not be included in the map, the inclusion or exclusion of specific concepts might group similar maps, for example, students who do or do not include anchovies with their pizza, students who prefer thick or thin crust, and so on.

Materials

Three tasks were defined for each participant. All students did a free-mapping task as an introduction to concept map construction in addition to the two language-constrained concept mapping tasks. Different materials were needed for each of the three tasks.

Materials for the Introduction to Concept Mapping

Students were introduced to concept mapping using a free-mapping task. A blank sheet of paper, 8.5 x 11, was provided for each student. Pencils and large erasers were available if needed.

Materials for the Pencil and Paper Task

The concept mapping worksheets for the pencil and paper task were copied on 8.5 x 11 white paper, landscape. The sheet was divided into three areas with two inches on the left and right for twenty concepts listed in ovals and four linking phrases listed in rectangles and labeled at the top of the page. The blank seven inches between the lists was labeled for the map. See Appendix B, Figure B1, for the pizza map worksheet.

Materials for the Computer-assisted Concept Mapping Task.

The Computer-assisted Concept Mapper (CCM) is a software program that provides users with a "toolbox" of concepts and linking terms to construct a concept map. The objective of the software is to provide an analog to the pencil and paper method of map construction while making it easy to modify connections and linking phrases. Data collection and comparisons between concept maps are facilitated by the use of language constraints. Features of The Computer-assisted Concept Mapper software (CCM) are described in Appendix B.

Protocol

The study was a two pronged test design consisting of a freely drawn practice concept map, a language-constrained map done with pencil and paper, and a language-constrained CCM map as shown in Figure 3.2.

The four participants at each grade level were briefly introduced to concept mapping techniques. Students were then given open-ended instructions for the free-mapping practice task. Students worked independently but were not isolated from one another. When finished with the free-mapping practice map, the participants were divided into two groups of two each. The first group did a paper and pencil map using constrained lists of concepts and linking words for the pizza domain, followed by a map of the domain using CCM with the same lists of concepts and linking words. The second group constructed a map using CCM, followed by a paper and pencil map using the same constrained lists of concepts and linking words.

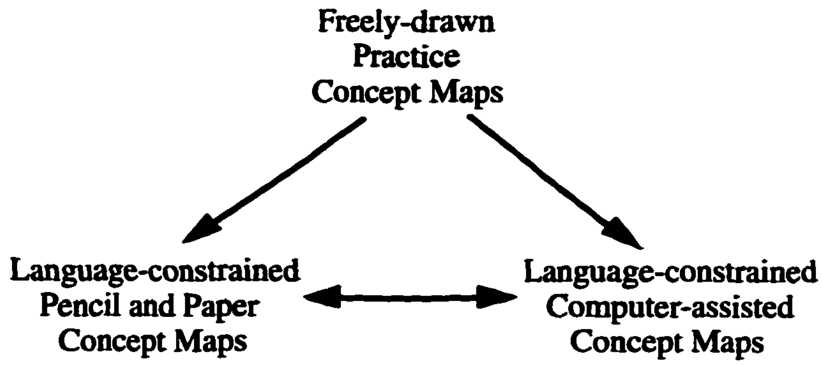

Figure 3.2. Design for the two way comparison of concept maps produced by each group of students at grade levels 6, 9 and 12.

Treatment for each grade level was conducted separately and on different days, following the same procedures. Student volunteers were identified by their teachers who released students from regular class work to go to a computer area with the researcher. Within a single class period of about one hour, participants at each grade level completed the introduction to concept mapping and the two language-constrained tasks.

Introduction to Concept Mapping

The introduction to concept mapping consisted of a brief discussion of how people see ideas linked together. Students were shown how to place the concepts in ovals, connect them with arrows in the direction that the statement should be read, and to write the linking words on the arrow. A few examples were given from another domain. Each student was then given a blank sheet of paper and asked to consider all the things they associate with a pizza meal and to show in their concept map how they see these ideas to be related.

Language-Constrained Computer-assisted Concept Mapping

For the computer task, students logged on to the network and began the CCM program under the direction of the researcher. They were given a sheet of step-by-step directions for the program and a brief hands-on lesson for adding concepts to the map, moving concepts, linking concepts together, and adding and changing linking phrases. Students were told they were not required to use all the concepts or linking phrases. This very limited introduction seemed to be adequate for most functions of the program.

Language-Constrained Paper and Pencil Concept Mapping

For this paper and pencil task students were given an 8.5 x 11 sheet with the same concepts and linking phrases used in the computer-assisted mapping task. They were asked to draw ovals for the concepts and use them only once, crossing them off the list of available concepts when used. Students were asked to link the concepts with a directional arrow and include the corresponding letter (a through d) of the linking phrase on the arrow to minimize the writing and time involved in map construction. Students were not required to use all the concepts or linking phrases.

Analysis of Maps

Comparison of Freely drawn vs. Language-constrained Concept Maps

This study accepts the validity of freely drawn concept maps as a tool to ascertain students' understanding of a domain and seeks to establish the validity of using CCM as a tool to produce language-constrained concept maps. A two way comparison of the language-constrained maps explores consistencies in the way relationships are represented in the language-constrained maps drawn with pencil and paper, and the language-constrained maps constructed with CCM.

The analysis seeks similarities and consistencies between the two types of maps. Several comparisons are made between the maps including the number of concepts used, number of concepts joined, specific concept pairs and relations that are formed, and the number of links to or from each concept. A count of the number of concepts and the number of concept pairs formed in the two maps of each student are listed for comparison in Table 3.2. Confidence in the average values is shown at the 0.05 level.

Although individuals may differ, the study also looks at group characteristics and calculates average values for each feature for each treatment group and for the combined treatment groups. Students in the treatment 1 group did the computer-based mapping first, followed by the pencil and paper mapping while the treatment 2 group did the pencil and paper mapping first, followed by the computer-based mapping. From the values in Tables 3.2 this study concludes that there is no significant difference at the 0.05 level between the paper and pencil and computer-assisted language-constrained concept maps in numbers of concepts used, or the number of relations either within or between treatment groups. This comparison leads to the conclusion that the two tasks, regardless of the performance sequence, produce maps that are not significantly different in the number of concepts used or relations formed. The following comparisons focus on additional properties of the two types of maps produced.

The average ratio of concepts to relations for the two types of concept maps indicates the overall branching or structural characteristics of the two maps. The ratio of concepts to relations for the pencil and paper task was 1.02 with a confidence of 0.04, while the ratio for the CCM task was 0.985 with a confidence of 0.059 at the 0.05 level. This study concludes that for branching or structural characteristics there is no significant difference between the paper and pencil and computer-assisted language-constrained concept maps.

Table 3.2
Comparison of Students' Selection of Concepts and Relations in Language-Constrained Maps Constructed with Pencil and Paper and Using The Computer-Assisted Concept Mapper (CCM) in Two Treatments.

		Paper and Pencil		CCM	
Treatment	Student	Concepts	Relations	Concepts	Relations
1	A	20	21	20	19
1	B	18	18	13	12
2	C	20	19	20	27
2	D	20	19	20	20
1	E	18	20	19	23
1	F	20	19	20	21
2	G	20	22	20	21
2	H	19	18	20	20
1	I	20	18	20	19
1	J	13	12	18	17
2	K	18	16	20	19
2	L	20	19	20	19
1	Average	18.17	18.00	18.33	18.50
	St. Dev.	2.71	3.16	2.73	3.78
	Confidence	2.17	2.53	2.18	3.02
2	Average	19.50	18.83	20.00	21.00
	St. Dev.	0.84	1.94	0.00	3.03
	Confidence	0.67	1.55	--	2.42
Combined	Average	18.84	18.42	19.17	19.75
	St. Dev.	2.04	2.54	2.04	3.52
	Confidence	1.15	1.44	1.15	1.99

Concept pairs selected.

This study has noted that the average number of concept pairs in both types of language-constrained maps are close, but are the concepts-connected the same way? At least some identical concept pairs are expected to be found in the two sets of language-constrained maps. Forty-four different concept pairs are identified among the paper and pencil maps, and of these just one concept pair, "Coke—beverage", was connected by all twelve students, but there were several pairs of concepts-connected by ten or eleven students. Forty-six different concept pairs were found among the computer-assisted concept maps, and of these, three concept pairs, "cheese—pizza", "pizza—meal", and "salad—meal" were connected by all twelve students. On the average, each student connected less than twenty concept pairs in either language-constrained concept map and considerable variation in concepts-connected is found when comparing the language-constrained concept maps of different students. These differences substantiate that language-constrained concept maps along with freely-drawn concept maps can represent students' unique knowledge structures.

Differences notwithstanding, both types of student maps have many concept pairs in common. This similarity can be captured in a mathematical ratio in which the number of concept pairs common to two maps is divided by the total number of unique concept pairs identified in the two maps. This similarity measure is an index of their global likeness or configurality. A comparison of each student's two efforts is expected to show stronger similarity. To get an overview of group similarity for the two tasks, the similarity ratio between each student's own maps is removed from the data set and will be looked at later in this study. A comparison between all other language-constrained paper and pencil maps and language-constrained CCM maps reveals an average similarity of 0.535 or 53.5% with a high of 0.900 and a low of 0.148. Although the range of data is further evidence of the uniqueness of maps, the average indicates a level of fundamental similarity. This study may conclude that here is some agreement in the concept pairs joined by these students.

The validity of language-constrained concept maps may be further established by an analysis of linking phrases in the two sets of language-constrained maps.

Comparison of linking phrases.

Relations are created when two concepts are linked by a phrase that defines their relationship. In both types of language-constrained maps, most concept pairs were found to be associated with two or three different linking phrases. Even when all students joined the same concept pair, at least one of the twelve students selected a different linking phrase to define the relation. The sixth and ninth grade students exhibited greater diversity in the selection of the linking phrases for each pair of concepts in the language-constrained maps. The twelfth grade students showed the highest agreement for the linking phrases selected for each concept pair in the computer-assisted mapping task.

When the maps are compared again, this time looking for similarities in concepts-connected and linking phrase selected, the similarity ratios for the two sets of language-constrained maps indicate an average of 0.284 or 28.4 % . The high was a ratio of 0.900 between maps of two twelfth grade students. The lowest ratio was a 0.028 or 2.8% correlation of linking phrases and concepts joined for a sixth grade and ninth grade pair of maps. Although a large number of different relations are identified, several students joined the same concepts using the same linking phrase for the relation. Similarity measures for concepts-connected and linking phrases selected indicate purposeful and meaningful connections as opposed to randomly selected connections between concepts. This basic agreement on the construction of relationships with concepts and links provided is accepted as further evidence for the validity of the language-constrained computer-based mapping tool.

Another way of looking at the data is offered in Table 3.3 which lists for each group of concept maps the total number of concept pairs and the number of concept pairs selected by all four students in the group, referred to as common concept pairs. When the linking phrase is included, more variation is introduced as expected. Table 3.3 lists the count of different relations (concept-linking phrase-concept units) and the number of relations selected by all four students in the group, and the average number of relations for each group.

The analysis shows for the number of concept pairs no significant difference at the 0.05 confidence level between the language-constrained maps constructed with pencil and paper and those constructed with The Computer-assisted Concept Mapper software tool (CCM). Overall there were slightly more concept pairs connected in the CCM maps, and slightly more variation in linking phrases selected for the relations in the paper and pencil maps, but these differences are not significant. There is also no significant difference found between the two types of maps for the average number of concept pairs that are common to all student maps of each type.

Table 3.3

A Comparison Concept Pairs and Relations in Paper and Pencil Concept Maps and Computer-assisted Concept Maps for Students in Grades 6, 9 and 12.

Group	Total Concept Pairs	Common Concept Pairs	Total Relations	Common Relations	Average Relations per Map
Grade 6 PP	36	6	78	1	19.25
Grade 6 CCM	40	5	53	2	19.50
Grade 9 PP	33	9	50	1	19.75
Grade 9 CCM	40	7	51	3	21.25
Grade 12 PP	24	5	35	1	16.25
Grade 12 CCM	21	16	31	7	18.50
Average PP	31	6.6	54	1	18.40
St Dev PP	5.1	1.7	17.8	0	1.55
Confidence PP	2.88	0.96	10.1		0.88
Average CCM	33.7	9.3	45	4	19.75
St Dev CCM	11.0	5.9	12.2	2.7	1.39
Confidence CCM	6.21	3.32	6.9		0.79

Another measure of the similarity of language-constrained maps is the comparison of links per concept, or concept connectedness which is explored in the next section.

Concepts most frequently linked.

Over all maps of each grade level, all concept pairs that include the concept are counted for this tally. For all three grade levels, the same concepts, pizza, meal, and meat, were the most-connected concepts in both paper and pencil and computer-assisted language-constrained maps. Beyond the first three concepts, the rank order of connectedness varies slightly among the grade levels. The number of links per concept drops off rapidly beyond the five most commonly linked concepts while maintaining close agreement in the number of links observed as shown in Table 3.4.

Table 3.4.

A Comparison of the Total Number of Links for the Most Used Concepts in Paper and Pencil and Language Constrained Concept Maps Constructed with The Computer-assisted Mapper by Students in Grades 6, 9, and 12.

	Total Number of Links						
	Pencil and Paper			CCM			Comp
Concept	Grade 6	Grade 9	Grade 12	Grade 6	Grade 9	Grade 12	St Dev
pizza	33	34	29	22	39	32	5.68
meal	16	15	12	15	15	16	1.47
meat	10	15	14	12	13	15	1.94
crust	9	12	11	12	8	12	1.75
beverage	9	9	10	7	9	11	1.33
cheese	6	7	5	12	5	6	2.64
Coke	7	6	5	5	5	5	0.84

Consistencies evidenced by the standard deviations between the two sets of language-constrained maps in the number of links for the most used concepts across all maps of the type is considered further evidence supporting the validity of the mapping technique since the same concepts are used in the same way in both representations.

So far this study has looked at group comparisons between all paper and pencil and computer-assisted maps. Further evidence of similarity between these two sets of maps can be seen in a comparison of each individual's two maps. Although this study has shown that each student's maps differ in some ways from maps of other students, the two maps constructed by each student show stronger similarities. In other words, each student's paper and pencil and computer-based maps are more similar to each other than they are to the efforts of other students. There is an average similarity ratio of 0.663 or 66.3% for concepts-connected in each student's two maps. The highest similarity was 0.947 for a twelfth grade student, and the lowest similarity ratio was 0.393 for a sixth grade student.

In all, three similarity measures were calculated for each student's language-constrained pencil and paper and CCM maps. The first calculation compares the similarity between concept pairs in the student's two maps; the second measure calculates the similarity between the two maps for concept pairs and the linking phrase joining them. The third similarity measure includes concept pairs, linking phrase, and directionality of the relations. The similarity ratios listed in Appendix C, Table C1, provide an index of the global similarity of each student's language-constrained maps to all other concept maps. Of particular interest are the relatively higher similarity ratios for each student's pair of maps, since this indicates that each student's efforts produce reasonably similar pencil and paper and CCM maps when using language-constrained concept mapping techniques. This finding suggests that language-constrained concept mapping using the computer-assisted mapping tool is a valid method of assessing students' structural knowledge.

A more molecular view of the similarities between each student's two maps examines the relations in each map. In this visual inspection, relations were considered to be a match if and only if three conditions were met: the concept pair, the linking phrase, and the directionality were the same in both maps. A partial match is identified when the same concept pair is found in both maps but joined by a different linking phrase, or if the directionality differed between the concept pair in the two maps. If a concept pair is found in only one of the two maps compared, a "no match" is declared. The results are shown in Appendix C, Table C1.

One sixth grade student connected the same eighteen concept pairs in both maps, but changed the linking phrase and/or directionality for six of the concept pairs in the second map. The other three sixth grade students changed the connections between concepts to join different pairs of concepts in their maps. The two efforts of these three students produced more idiosyncratic renditions of their language-constrained maps than was typical of the ninth and twelfth grade students. The sixth grade students have been shown to have the lowest average similarity ratio 0.535 for the comparison of concepts-connected in their two efforts. A higher correlation was found in comparing the two language-constrained maps of ninth and twelfth grade students, especially in the comparison of concept pairs selected. Student H joined many of the same concept pairs, but selected different linking phrases for many relations in the two maps; the similarity ratio for concepts-connected in her two maps is 0.750, but when linking phrases are included in the comparison, the similarity ratio for her two maps drops to 0.312. Twelfth grade students I and L had virtually identical maps with minor variations in their pencil and paper and CCM maps; their similarity ratios for concepts-connected and same links in both maps are the highest for all students at 0.947 for student I and 0.900 for student L. These findings suggest that language-constrained computer-assisted concept mapping produces valid results.

Summary

In summary, to establish the validity of the computer-assisted mapping assessment using a constrained set of concepts and links, one could argue that the relations between the number of concepts and the ways they are related would be similar in the both the paper and pencil and the CCM language-constrained maps.

1. Comparisons in this study show that the number of concepts used and number of relations in the two sets of language-constrained maps were very similar.

2. Structural characteristics of the two types of maps are similar as indicated by the finding in Table 3.2 that shows no significant difference between the two types of maps in the ratio of concepts used to the number of relations.

3. An average similarity ratio of 0.535 between the two types of maps for concepts-connected supports the similarity of language-constrained pencil and paper and computer-assisted maps.

4. The range of the similarity ratios provides evidence of the variation in selection of concept pairs and linking phrases. Despite the use of constrained lists of concepts and links, different students construct uniquely different representations of the relationships they see between concepts. Variation in concepts-connected and linking phrases selected produce language-constrained maps that are unique representations of each student's way of seeing connections between these ideas. Uniqueness is a characteristic of freely-drawn traditional concept maps, and is to be expected in valid concept maps. Since uniqueness of individual knowledge structures is reflected in unique representations in freely-drawn concept maps, the observed variations between the language-constrained concept maps of different students also supports the validity of this mapping technique in its ability to produce unique concept maps.

5. The total number of concept pairs, number of common concepts paired, number of relations, and common relations indicate no significant difference between the two

types of maps at the 0.05 confidence level as shown in Table 3.3. This finding supports the validity of language-constrained concept mapping.

6. The same set of seven concepts were most-linked in both types of maps, and the number of links to each concept across all maps of each type were similar for both types of maps as shown in Table 3.4. This similarity between the two types of maps supports the validity of language-constrained concept mapping.

7. Comparisons between each individual student's two maps indicates a higher similarity between their own two maps than to the maps of other students. Based on similarity calculations, this study concludes that similar concept maps are produced by each student whether using paper and pencil or the computer-assisted mapping tool. The consistency of each student's map representation in two different tasks supports the validity of language-constrained concept mapping.

The next study tests the reliability of the method to determine whether students using only the computer-assisted mapping tool and a set of language-constrained concepts and linking phrases will construct reasonably consistent concept maps in repeated efforts.

Study 2: Reliability of Language Constrained Concept Mapping Over Time

Overview

Using The Computer-assisted Concept Mapper software (CCM), a group of students mapped the same set of instruction-free concepts and linking phrases in two sessions one week apart.

Participants

Fifteen sixth grade students from one intact computer keyboarding class participated in the study of language-constrained computer-assisted concept mapping over time. All students were present for both scheduled sessions. Nine girls and six boys comprised this group.

Concept Selection

This study required two sets of concepts and linking phrases, the first for the introductory experience, and the second for the comparison of mapping over time. An instruction-free domain was selected for this study so that mapping would not be influenced by learning in the interval between sessions. The concepts used for the introduction needed to be sufficiently different so as not to sway student choices in the actual study, while some of the same linking phrases were used in the introduction to exemplify proper usage of the terminology. Fourteen concepts related to animals were selected for the introductory lesson: animal, dog, cat, wolf, domestic, wild, mammal, reptile, bird, fur, feathers, scales, robin, and red. Three linking phrases were used for introductory task: "is a part of", "is a characteristic of", and "can be". The individual student maps in both sessions used the same twenty pizza meal concepts and four linking phrases as were used in study 1.

Materials

The introductory concept mapping task with the group was done at the blackboard in the computer lab. Students used the CCM computer program for computer based concept mapping as described in study 1.

Protocol

Session I

Students were briefly introduced to concept mapping with a discussion of how people link ideas together, followed by a group mapping experience using the non-instructional domain based on animals. While students suggested ways to link the available concepts, the researcher drew the map on the blackboard, demonstrating how to write concepts in oval shapes and how to connect concepts together with directional arrows and linking phrases. Discussion and examples were used to clarify the distinction between "is a part of" and "is a characteristic of", two of the four linking phrases that would be used in the study.

Students were next given a brief tour of the CCM program and allowed a few minutes to explore the functions of the program. Students then worked independently on the computers to construct their maps of the pizza domain. Each student was asked to use a unique code that included a session identifier for her saved map. The first session included the introduction to concept mapping, introduction to the computer program, and the individual mapping task. The entire first session was completed within a single 45 minute class period.

Session II

The second session a week later consisted of a brief review of program features and new mapping session where students were asked to repeat the mapping task with the same set of concepts and linking phrases they had used in the first session. Most students completed the mapping task in Session II within 30 minutes. Two students did not finish the mapping task. One student decided that he did not know how to include the remaining concepts and asked to stop about ten minutes before the end of the session; the other student worked at the mapping task until the end of the class, but was unable to finish.

This student had requested help with program functions requiring facility with the mouse such as linking concepts and making changes to the map.

Analysis

This analysis focuses on the comparison of each student's map from Session I with the map constructed a week later during Session II. The reliability of the technique is somewhat dependent on time. The introductory lesson on concept mapping left students with less time to work on the actual concept maps during the first session. The time allocated to the mapping task in the second session was about fifteen minutes longer than the time available during session I. More concepts were used and linked in the second set of concept maps as expected. Two additional factors probably impacted the production level of each student, both related to use of the computer tool. The first factor was the student's manual dexterity with the mouse, and the second factor, their ability to adapt their skills to move and connect objects in the computer program. Some of the students were not accustomed to using the mouse as intensively and skillfully as the CCM program requires, and these students generally had difficulty learning to move concepts on the screen and to master the concept linking. These less adept students were unable to construct a complete concept map in the short time available.

The important finding that this study looks for is that the concepts used in the first map are used in the second map, and that the concepts linked in the first map are again linked in the second map. As a natural consequence of the first effort, students have more facility with the program, and have had at least some practice in developing dexterity with the mouse as they approach the second mapping effort. To this advantage is added the bonus of more time available for the task. Most students, even those who have difficulty with the mouse functions, are expected to complete the second map by using most of the concepts; however, the first map most likely was unfinished.

For an instruction-free domain, when all concepts are not used, a comparison of the first to the second map predicts three findings: first, all the concepts used in the first map will be found in the second map; second, in both efforts, students will tend to connect most concepts in the same way, so that a high proportion of the same relations will be found in the second map. Third, few relations that were present in the first map will be missing in the second map.

The number of concepts used by each student for maps constructed in Session I and in Session II is shown in Table 3.5.

Table 3.5
Number of Concepts Used by Each Student in Maps Constructed in Two Identical Mapping Tasks One Week Apart Ranked by Difference.

Student	Session I Concepts	Session II Concepts	Difference
BBB	20	20	0
III	18	20	2
LLL	17	20	3
GGG	7	13	6
MMM	14	20	6
EEE	12	20	8
HHH	12	20	8
NNN	11	20	9
DDD	5	15	10
PPP	9	19	10
KKK	10	20	10
AAA	8	19	11
JJJ	9	20	11
FFF	6	19	13
CCC	5	20	15

On the average, students used about eleven concepts in Session I maps, and nineteen concepts in Session II maps. Only one student, BBB, used all twenty available concepts in both sessions, but ten students used all concepts in Session II. Student CCC had the largest difference, using just five concepts in the first map and twenty in the second.

The occurrence of concepts used in the two sets of maps is shown in Figure 3.3. For Session I maps only two of the available concepts were selected by all students for inclusion in their maps, and six concepts were most commonly selected by students: "meal", "pizza", "crust", "pepperoni", "Coke", and "salad". In the Session II, all students used "meal", "pizza", "crust", "pepperoni", "tomato sauce", "cheese", "sausage", and "anchovies" apparently focusing on the pizza ingredients.

A comparison of each student's two efforts shows that all concepts used by any student in Session I were again selected by that student in Session II; however, more concepts were added during the Session II map construction exercise. Since the number of concepts differed considerably for the two maps constructed by each student, the similarity ratio for concepts used is correspondingly low. The similarity ratio is calculated by comparing the size of the common set of concepts to the total set of concepts. If a student selected five concepts in the first session and used all twenty concepts in Session II, the ratio of concepts used would be 0.200 or 20.0%. In some cases, the similarity in the number of concepts used is higher between one student's second map and the map of another student who used a more concepts in the first effort. Although the similarity measures are reported in Appendix D, this analysis shows that when there are large differences in the number of concept pairs in the student's two efforts, the large divisor in the similarity ratio, equal to the union of all concept pairs identified in the two maps, masks the information that is sought. The similarity ratios for concepts used in maps for Session I and Session II are listed in Appendix D, Table D1.

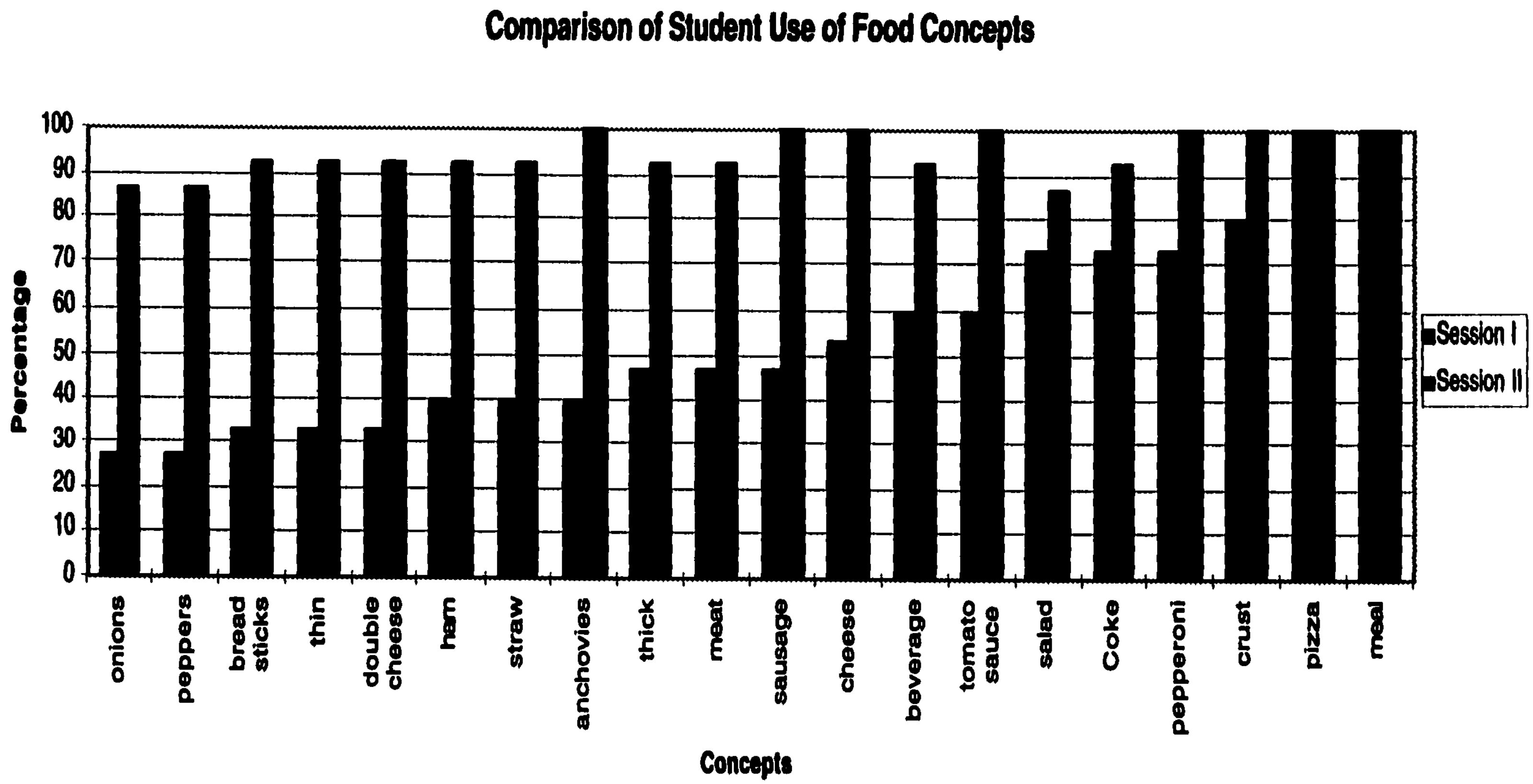

Figure 3.3 A comparison of concept occurrence in maps constructed in two sessions one week apart.

The similarity ratios for concept pairs or concepts-connected are listed in Appendix D, Table D2. The number of concept pairs common to each student's maps from Session I and Session II is divided by the total number of concept pairs in the two maps to calculate the similarity ratio.

Appendix D, Table D3 lists the similarity ratios for relations found in the two maps. Not only must the concept pairs match, but also the linking phrase selected to explain their relationship. Appendix D, Table D4 shows similarity ratios for global configurality of the maps including concepts used, concepts joined, linking phrases, and direction of the links.

The relatively large differences in the scope of the two maps constructed by each student dilutes the similarities between them when the similarity measure is calculated. An inspection of the specific relations used in each student's maps reveals concrete similarities found in the two maps. This analysis focuses on each relation found in the first map and whether it is exactly matched, modified by selection of a different linking phrase or direction of the link, or whether the relation is missing in the second map constructed by the student one week later using CCM. Findings are reported in Table 3.6.

Table 3.6

Comparison of Concept Relations in Sixth Grade Student's Concept Maps Constructed in Two Sessions One Week Apart

Student	Relations in Map I	Relations in Map II	Relations Matched	Relations Modified	Relations Missing
DDD	4	15	2	1	1
CCC	4	19	1	2	1
FFF	5	18	3	2	0
GGG	6	13	4	2	0
AAA	7	18	3	2	2

Table 3.6 (continued)

Comparison of Concept Relations in Sixth Grade Student's Concept Maps Constructed in Two Sessions One Week Apart

Student	Relations in Map I	Relations in Map II	Relations Matched	Relations Modified	Relations Missing
PPP	8	18	7	0	1
KKK	9	19	3	3	3
JJJ	9	23	1	1	7
EEE	10	19	2	6	2
NNN	10	20	8	1	1
HHH	11	19	2	4	5
MMM	13	19	8	1	4
LLL	17	19	7	5	5
III	18	19	12	2	4
BBB	22	19	7	4	11

Table 3.7 summarizes the findings detailed in Table 3.6.

Table 3.7

Percentage Recurrence in Second Concept Map Constructions of Concept Relations Shown in First CCM Concept Maps of All Sixth Grade Students

	Relations in Map I	Relations Matched	Relations Modified	Total Matched	Relations Missing
Count	153	70	36	106	47
Percentage	100	45.8	23.5	69	30.7

This analysis shows that across all maps, 69% of the concepts-connected in the first map are again connected in the student's second map. This evidence supports the reliability of language-constrained computer-assisted concept mapping since the representations are reasonably consistent.

Summary

A comparison of the maps in a test/ re-test design shows similarities between maps based on concepts linked, linking terms, and directionality of the links.

1. Forty-six percent of the relations included in the students' first maps are identically represented in the second set of maps constructed a week later.

2. Twenty-three percent of the concept pairs included in the students' first maps are found in the second set of maps constructed a week later, but the relations had been modified by the selection a different linking phrase and/or the direction for the relation.

3. When the first and second sets of maps are compared, the ratio of identically represented relations to the relations modified by selection of different linking phrase or directionality of the link is about 2:1.

4. Overall, sixty-nine percent of the concept pairs identified in students' first maps are found in the second set of maps constructed a week later.

5. Less than thirty-one percent of the relations identified in students' first maps are missing in the second set of maps constructed a week later.

6. When the first and second sets of maps are compared, the ratio of recurring concept pairs to missing concept pairs is about 2:1.

These comparisons show that the relations represented in each student's first map show reasonable stability in the second effort, a finding that supports the reliability of language-constrained concept mapping.

Although the validity and reliability studies have limited the number of participants to twelve and fifteen students respectively, the next study will look at the ratios of concepts and relations of the language-constrained concept maps of 378 students. This study analyzes these sixth, ninth, and twelfth grade student maps for similarities and differences and to see whether more complex map structures are grade related unless some variable intervenes such as the chunk of the curriculum that includes this domain.

Study 3: Discrimination Ability of the Tool

Overview

This study tests whether a concept mapping task utilizing the language-constrained computer-assisted concept mapping tool can be used to discriminate students on their knowledge of the domain. A large number of participants from grade six, nine, and twelve constructed CCM concept maps using the same set of concepts and linking phrases. Similarity measures are used to identify maps that represent relations in the same way; and cluster analysis is used to sort groups of similar maps. Inspection of the clusters reveals patterns of similarity within the clusters and differences between clusters.

Participants

The following Table 3.8 shows the distribution of students participating in study 3 and study 4. The total of 378 students included 203 sixth grade students, 57 ninth grade, and 118 twelfth grade students from twenty science classes taught by six teachers.

Table 3.8

Distribution of Participating Students by Class, Grade Level, and Gender.

Teacher	Grade Level	Number of Classes	Boys	Girls	Total Students
Teacher A	6	2	10	20	30
Teacher B	6	4	49	51	100
Teacher C	6	4	32	41	73
Teacher D	9	3	29	28	57
Teacher E	12	5	58	32	90
Teacher F	12	2	14	14	28
Totals	3	20	192	185	378

Concept Selection

Process of Concept Selection

Concept maps for this study used two domains. The pizza domain was used for the introduction to concept mapping. A second domain for the study was chosen for its relevance to the K—12 science curriculum since the maps would be used to test the discrimination ability of the tool and to identify levels of deepening understanding. The domain selected for this study had to fulfill several prerequisites. The concepts should be taught in grades kindergarten through twelve, or more specifically grades five through twelve so that developmental differences and levels of understanding within this domain might be identified for students at these grade levels. Since this study is not coupled to the effectiveness of instruction immediately preceding or following the concept mapping task, the concepts selected for the study should be included in the required curriculum and assessment for grades five through twelve. Several resources were consulted in identifying a domain that had the desired scope and sequence. The Michigan Essential

Goals and Objectives for Science Education (K—12), the MEAP Blueprint and Proficiency Framework, and Options for Science MEAP Area-Specific Assessments for Grade 5 and Grade 8, Science for All Americans, and NSTA charts and materials were taken as evidence that Atmosphere and Weather/Patterns of Change are components of the benchmarks for the physical science/earth science curriculum for grades five and eight for the local school district.

The domain of choice should discriminate a difference in understanding among students over a range of grade levels. The expectation was that students would study weather in the ninth grade earth science, that students would develop a deeper understanding of relationships between biological processes and water vapor in biology class, and that concepts involving the relationship of water vapor to air density and barometric pressure, and thermodynamics of phase changes would be developed in chemistry and physics classes that are usually taken in grades ten through twelve.

Based on this information and premises, the researcher selected from the curriculum materials concepts relating to the water cycle, drew a concept map, and from it extracted a construction set of concepts and links. The six participating teachers were asked to test the feasibility of the prototype construction set by drawing a concept map. One sixth grade teacher offered an NSTA chart of the water cycle that was particularly valuable in bringing a fresh perspective to processes relating to the water cycle. As a result, several process concepts were added to the construction set. Based on teacher maps and recommendations, a revised list of thirty concepts and fourteen linking phrases was developed. The fourteen linking phrases were later pared to a list of ten to fit the constraints of the computer-assisted mapping program at that time. A final set of thirty concepts and ten linking terms was accepted for use in the study. See Appendix B, Table B1, for the complete list of water cycle concepts and linking phrases used in the study.

Description of Concepts and Linking Phrases Selected

A broad range of concepts relating to the water cycle was selected to provide the means of discriminating levels of understanding among the students. About half of the concepts selected were considered to be basic concepts that were expected to be familiar to most students from common experience and knowledge, and about half were process or other more complex concepts that were predicted to be more likely understood and included in maps of more advanced students who had taken high school earth science, biology, chemistry, and physics classes.

Concepts are usually nouns, but, in this study, four verb concepts were included: infiltrates, condenses, melts, and freezes. The simpler word condenses was preferred to the noun condensation, and infiltrates was preferred to infiltration. Linking phrases were provided to create meaningful statements relating these verbs concepts to other concepts; however, the very fact that these concepts were verbs meant that use of a linking phrase was not imperative in order to connect these concepts to other concepts, and many students elected to omit linking phrases for these concepts.

Four concepts selected were hybrids linking two related concepts together: lakes and rivers, land or soil, season and climate, dust/air pollution. The combination of terms was intended to broaden the application of the concept. Nine process concepts were included: evaporation, precipitation, combustion, respiration, transpiration, infiltrates, melts, freezes, condenses. Forms of water, water vapor, cloud, snow, ice, rain, frost, fog, ground water, run off were among the concepts included.

Ten linking phrases were used in this study. Three of the linking phrases incorporated variations: “is/are”, “produces/forms”, and “into/in”. Three diametric pairs accounted for six linking phrases: “has effect-increases” paired with “has effect-decreases”, “released heat energy” paired with “absorbs heat energy”, and “rises into” paired with “falls on”. The tenth linking phrase was “is a cause of”.

Materials

Materials consisted of a transparency for the introductory concept mapping task, worksheets for the pencil and paper exercise, and the CCM computer program for computer based concept mapping as described in study 1.

Protocol

All classes were given the same introductory experience before beginning their individual map tasks. The pizza theme was used for a group lesson. Concepts were mapped using a 11x 8.5 transparency designed to match the layout of the individual mapping task. Twenty oval shapes were drawn within two inches in left margin, one concept per oval, and numerals identified each oval in the sequence. Four linking terms were listed within the two inches of the right margin, each phrase printed in a narrow rectangle. The map was drawn in the center area of the transparency. A black marker was used to draw the concepts and label the links as students suggested relations to be added to the map. When at least half of the concepts had been used in the map and students seemed comfortable with the procedure and ready to try their own maps, students were given directions for the individual mapping task.

The paraphrased instructions given to students are included in Appendix B.

A computer lab was not available for the sixth grade students. These students generated individual maps using paper and pencil methods. The concept mapping worksheets were copied on legal size pastel colored paper. The general layout used was identical to the transparency used for the introduction, and the same format as the screen for the computer-based mapping. Thirty concepts and ten linking terms related to the water cycle were used for the study. See Appendix B, Figure B2, for the water cycle map worksheet.

It is important to note that while giving the instructions for the task, no question was posed or statement made to guide students in forming a framework for the relations between concepts. Water was the first concept in the list, but students were told that they could begin with any concept. Eleven of the 378 students chose not to include the word water in their concept map.

Coding

For pencil and paper maps, each concept was assigned a number in the original list, and each linking phrase was identified by a letter. Students were taught how to encode their maps and were invited to write the encoding for the triads at the bottom of their maps if they had the time and wanted to do it. All codes from paper and pencil exercises were rechecked and verified by the researcher before being entered by the researcher into computer text files, one triad per line, for analysis.

For computer-based concept maps, codes were generated by the computer when the maps were saved within the program. Relations represented in each map were encoded into triad lists and saved as a text file with a unique filename composed of five fields identifying course, teacher, hour, gender, and a sequence number to differentiate students. For example, PV1F36 identifies a Physics student of teacher Vee, first hour, female, participant number 36.

Analysis

The content and construction of the concept maps are compared to discover similarities between maps of each grade level. The elements of concept maps, concepts, links, and directionality, provide the fundamental basis for these comparisons. At the first level of analysis the research examines the number of concepts used, which concepts were used, and the frequency of occurrence of each concept for each grade level. The similarity measures for concepts used are calculated for all pairs of maps, and the maps are clustered based on similarities in concepts used. The characteristics of each of these clusters are investigated to see the extent to which this level of analysis can discriminate maps.

The second level of analysis of the maps looks at the connections between concepts in maps at each grade level. The number of concept pairs, the specific concept pairs and their frequency of occurrence at each grade level are compared. All concept maps are also compared for similarities in concepts-connected, and clustered on the basis of these similarity measures. Characteristics of these clusters are compared to reveal differences between the clusters and similarities within clusters.

Following this scheme, analysis would next look at the linking phrases used to describe relations between concept pairs, and the direction of each of the relations in each concept map. For reasons to be explained later, this research limits analysis to the concepts. This study now proceeds to find whether this method of analysis can, for large numbers of student concept maps, discriminate levels of understanding of a domain.

Analysis of the Number of Concepts Used

Since students were not required to use all concepts provided, the lowest level of analysis examines first the number of concepts used, and then specifically which concepts were used by students at each grade level. For the first level of analysis, the number of concepts used by students at each grade level is compiled and averaged. The number of concepts used by each student ranges from six to thirty and increases slightly by grade level from an average of 14.6 concepts used by sixth grade students, 16.4 used by ninth grade students, to an average of 18.4 used by twelfth grade students. Table 3.9 shows the average number of concepts used by students at each grade level at a confidence level of 0.05.

Table 3.9

Average Number of Concepts Used by Students in Grades 6, 9 and 12.

	Grade Level		
	6	9	12
Average Concepts	14.66	16.40	18.35
Confidence	0.680	1.408	1.177

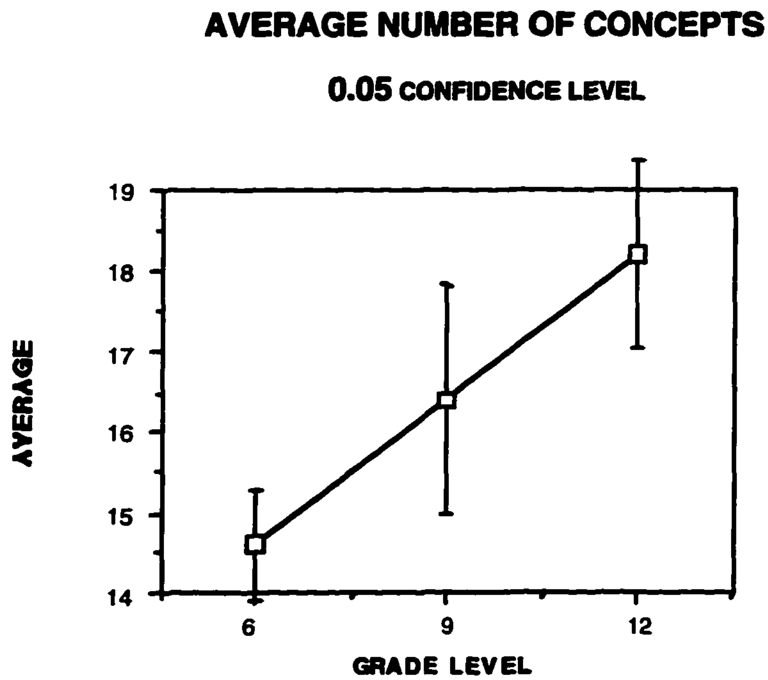

Figure 3.4. Graph of the average number of concepts used by students in grades 6, 9 and 12 showing the interval for a confidence level of 0.05.

The graph in Figure 3.4 indicates a significant difference between the number of concepts used by sixth and twelfth grade students, but no significant difference when the ninth grade students are compared to the sixth and twelfth grade students. None of the sixth grade students used all thirty concepts, and only one sixth grade student used twenty-nine concepts. Six of the sixth grade students used only six concepts. One ninth grade student used all thirty concepts and only one ninth grade student used only six concepts. Eight twelfth grade students used all thirty concepts and one twelfth grade student used only six concepts for their concept map.

This first analysis looks only at the number of concepts used by students. Certainly, students using ten concepts, for example, from the list of thirty provided will not necessarily choose the same ten concepts, although considerable overlap in the sets of concepts selected is expected. The next step in this first level of analysis examines which concepts are used by students at each grade level.

Analysis of Specific Concepts Used

The next question focuses on which concepts are used by students at each grade level and asks whether there is a difference in the set of concepts used by students at different grade levels. Figure 3.5 shows the percent occurrence for each concept ranked in order of percent occurrence for twelfth grade students. The graph in Figure 3.5 shows that even for the least used concepts for all students, nearly twenty percent of twelfth grade students included these concepts in their maps. Twelfth grade students have the highest percent occurrence for twenty-two of the thirty concepts, having on average used more concepts in their maps than the sixth or ninth grade students. Ninth grade earth science students included the concepts of "run off", "ground water", "lakes and rivers", "land or soil" more often than sixth or twelfth grade students in this study. Sixth grade students had the highest percent occurrence of any group, if only by a small margin, for the concepts "water", "rain", and "cloud". Very few sixth and ninth grade students used the process concepts of "transpiration", "combustion", "respiration", or "infiltrates" in their maps. In addition, the terms "separate molecules", and "atmospheric pressure" are used by less than forty percent of any group.

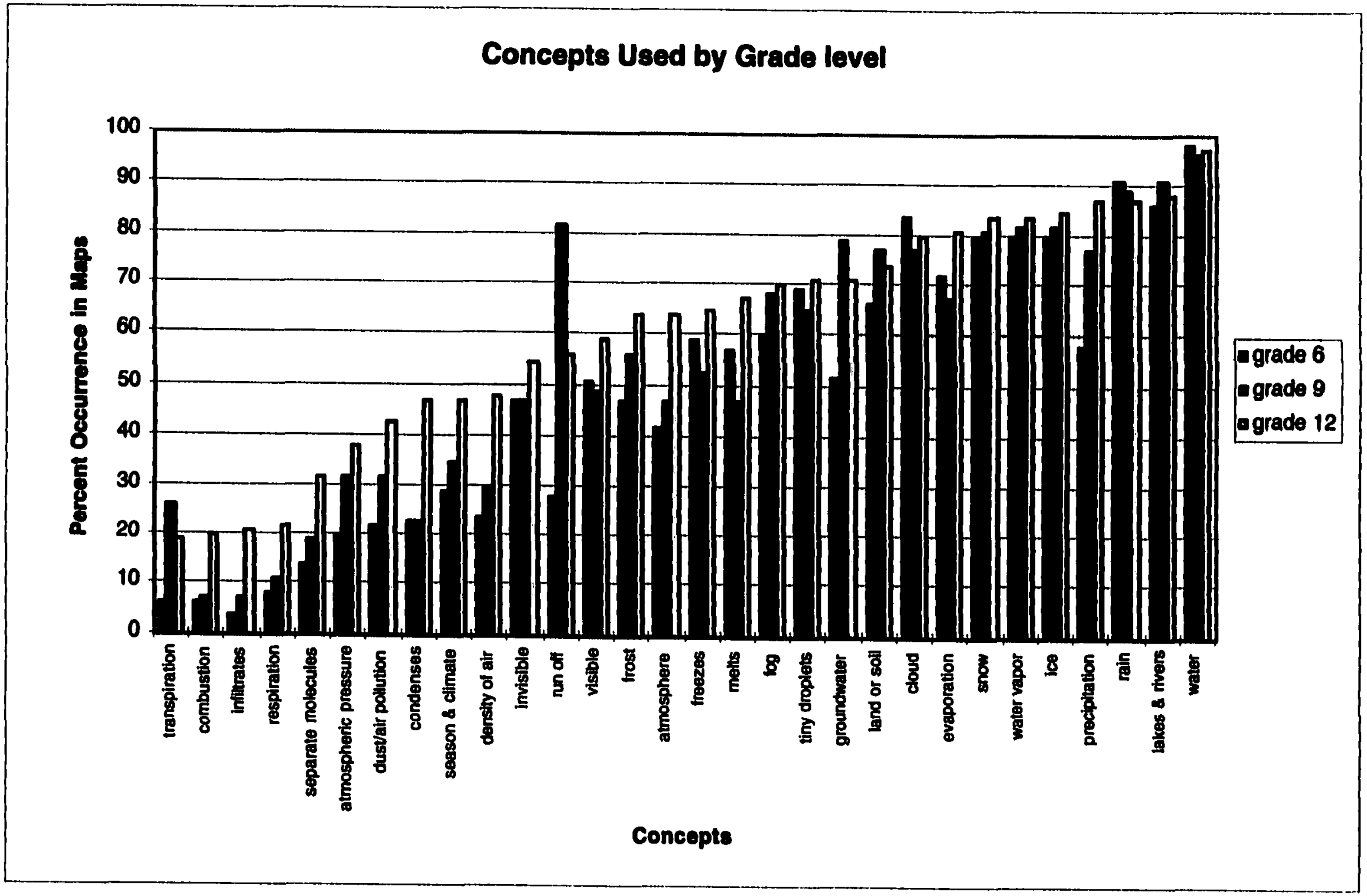

Figure 3.5. Comparison of percent occurrence of concepts in student maps of each grade level.

This step in the analysis gives an overall pattern of use of concepts; however, individual students used various combinations of these concepts in their maps. An analysis of the sets of concepts selected provides a more useful measure of levels of understanding. Since the overall pattern of occurrence of concepts seems to follow a similar trend for all grade levels, some sixth, ninth, and twelfth grade students are expected to select similar groups of concepts for their maps. Therefore the next test of similarity between concept maps for concepts used includes all students rather than students by grade level as described in the next section.

Comparison of Concept Maps for Similar Concepts Used

This analysis compares all 378 student concept maps for similarities in the concepts used. For this level of analysis the study considers only the set of concepts used by each student and not pairs of concepts-connected. Therefore, an ordered list of the concepts used is extracted from each student's list of triads represented in their map. Each concept set is compared to every other student concept set and the similarity ratio calculated. The similarity ratio is defined as the number of matches between two maps divided by the magnitude of the set compared. For example, if one student used concepts 1, 2, 3, 5, 15, 20, 23, 29 and another student used concepts 1, 2, 5, 15, 17, 23, 25, 29, the combined set is 1,2,3,5,15,17,20,23,25,29 or 10 members. The set of common concepts is 1, 2, 5, 15, 23, 29 or 6 members. The similarity ratio for the two maps is therefore 6/10 or 0.600. A ratio of 1.0 is a perfect match of identical maps based on the characteristic in question, in this case, concepts used. A ratio of 0 is a null match where no similarities were detected between the maps; in that case, the students would have used totally different sets of concepts in their maps.

Similarity ratios were found to occur as a normal distribution as shown in the sample histogram in Figure 3.6. This particular example shows low similarity ratios.

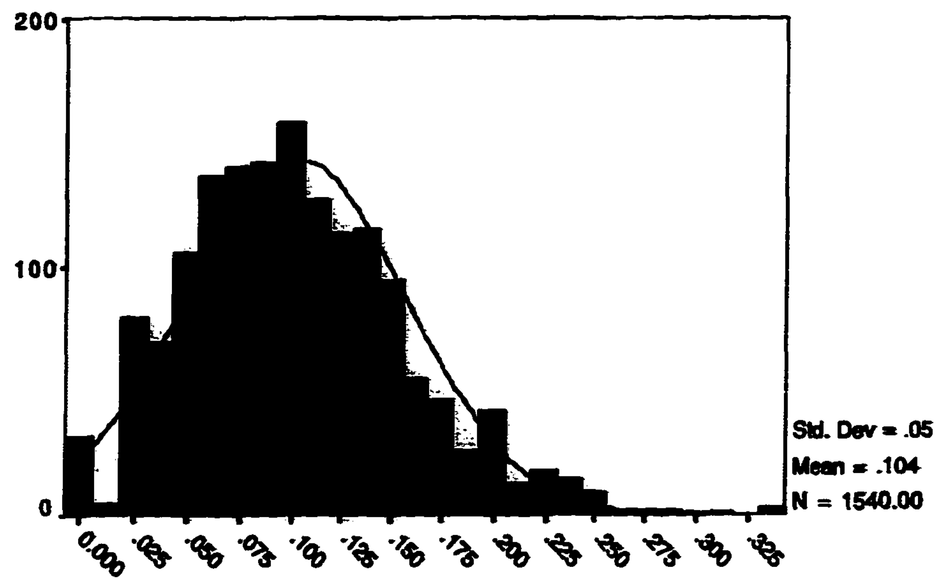

Figure 3.6. A histogram of the similarity ratios shows a normal distribution curve.

For large groups of students, even knowing the similarity ratio for all pairs of maps does not make it a simple matter to identify smaller groups of similar maps. This can be accomplished with cluster analysis, which determines the number of groups and the membership in each. Cluster analysis produces homogeneous groupings based on the data provided, even when the desired number of groups is unknown, as in this kind of analysis. Only one type of variable is used to sort the concept maps, the similarity ratio, so all data is uniform.

At this first level of comparison, the similarity ratio compares the set of concepts used in each map with the set of concepts in every other map. A triangular matrix is formed by values of similarity ratios for all pairs of concept maps for all 378 participating sixth, ninth, and twelfth grade students. The matrix of similarity ratios is then converted to a distance matrix (1-x) which describes how far apart the values are.

Hierarchical cluster analysis was selected because it shows how the individual maps form small clusters, and how these clusters combine into increasingly larger clusters until the whole group is joined. If the number of small clusters is unwieldy, larger clusters in the hierarchical structure can be easily identified and compared. For this study, the selected procedure for determining cluster membership is Ward's Method in which the means for all variables are calculated. The squared Euclidean distances to all other means in the cluster are calculated for each member. Mergers are formed to include members that produce the least increase in the sum of the squared Euclidean distances within the cluster. (Norusis, 1994. p.98).

The dendrogram resulting from the application of Ward's Method to this set of data reveals nine clusters at the first level of hierarchy when maps were compared for similarities in concepts used. Further aggregation to reduce the number of clusters to a manageable number for further study was not necessary. The characteristics of these nine sets of map clusters are described in the next section. Clusters are examined for size of membership, grade-level membership, and average similarity ratio. The specific concepts used in maps of each cluster are examined to determine the average number of concepts, concepts used, and missing concepts.

Membership and similarity ratios of same-concept clusters.

Each of the nine clusters of maps are compared for cluster size, average number of concepts per map and similarity ratios. The average and standard deviation for the similarity ratios for each cluster are listed in Table 3.10. The maximum and minimum similarity ratios found in each cluster are provided as a further indication of the range of similarity ratios within the cluster.

Table 3.10

Cluster Size, Number of Concepts, and Similarity Ratios of Same-Concept Clusters Ranked by Average Number of Concepts

Cluster	Size	Average Number of Concepts	Average Similarity Ratio	Standard Deviation	Maximum Similarity Ratio	Minimum Similarity Ratio
1	26	7.5	0.254	0.145	1	0
4	38	10.2	0.380	0.112	0.900	0.105
3	21	10.3	0.431	0.106	0.889	0.200
8	35	13.2	0.636	0.089	1	0.421
9	74	14	0.576	0.097	0.938	0.316
2	31	14.5	0.418	0.097	0.846	0.130
7	63	18	0.607	0.089	0.944	0.375
5	57	22.8	0.837	0.076	1	0.536
6	33	26.5	0.833	0.110	1	0.600

All 378 maps are compared for similarities in concepts used on the premise that some sixth, ninth, and twelfth grade students might choose the same concept sets. The cluster membership by grade level is examined next. Since the population of the grade level groups varied considerably with 203 sixth grade, 57 ninth grade, and 118 twelfth grade students, a percentage of each grade level represented in each cluster is indicated along with the actual count in Table 3.11.

All three grade levels are represented in each cluster. The clusters one through four appear to have about the same percentage of each grade level represented, but clusters five through nine show more variance in composition by grade level. Cluster 5 contains about 20% of all twelfth grade students. Cluster 6 has only 3% of all sixth grade students. Cluster 7 has about 23% of all ninth grade students, and Cluster 9 has about 25% of all sixth grade students. Cluster 8 has only about 4% of all twelfth grade students.

Table 3.11

Cluster Membership Distribution by Grade Level Showing Percentage of All Grade Level Participants in Clusters Sorted by Increasing Number of Concepts

	Grade				Percentage of Grade		
Cluster	6	9	12	Total	6	9	12
1	13	3	10	26	6.4	5.3	8.5
4	23	4	11	38	11.3	7.0	9.3
3	13	3	5	21	6.4	5.3	4.2
8	24	6	5	35	11.8	10.5	4.2
9	51	10	13	74	25.1	17.5	11.0
2	18	5	8	31	8.9	8.8	6.8
7	28	13	22	63	13.8	22.8	18.6
5	27	6	24	57	13.3	10.5	20.3
6	6	7	20	33	3.0	12.3	16.9
Totals	203	57	118	378	100.0	100.0	100.0

These same-concepts clusters are arranged in order of increasing numbers of concepts used. Is there a pattern in the distribution of students across grade levels? The trend is clearer if clusters are divided into groups of high and low numbers of concepts as shown in Table 3.12.

Table 3.12

Percentage Distribution of Students with Concept Maps in the Lowest and Highest Clusters Ranked by Average Number of Concepts Selected

	Grade Level		
Clusters	6	9	12
Lowest 4	36.2	28.1	26.2
Highest 4	39.0	54.4	62.6

Table 3.12 summarizes the distribution pattern in the same concept clusters. This evidence shows that the distribution of sixth, ninth, and twelfth grade students decreases by increasing grade level for the lowest four clusters, and increases by increasing grade level for the highest four clusters. The sixth grade students are found in higher percentages in clusters having the lowest number of concepts. Ninth grade and twelfth grade students are more likely to be found in the clusters having the highest numbers of concepts.

In the next section, the specific concepts used or missing in each cluster are examined to see whether cluster analysis based on similarity ratios for concepts used discriminates between maps.

Distinguishing characteristics of same-concept clusters.

The description of each of the nine clusters focuses on observed characteristics common to each group as well as unique characteristics that set them apart from other clusters. Clusters can be distinguished on the basis of concepts included, missing concepts, average number of concepts, and average within-cluster similarity ratio.

Cluster 1—No concept map in Cluster 1 includes the concept "combustion". The highest percentage is 88% for the concept "water", the only concept used by at least seventy-five percent of the students; five concepts were each used by only one student in the group. This group of 26 students used few concepts in their maps and there is little agreement in concept usage within the cluster. Less than 9% of each grade level is represented in this group.

Cluster 2—This cluster shows better agreement in concept usage. All of the concepts included in this set of maps were used by at least two of the students; no concept appeared in only one map. The highest percentage occurrence for any concept was 97% for "water". Four concepts, "water", "lakes and rivers", "land or soil", and "rain" were used by at least seventy-five percent of these 31 students. Cluster 2 students on average used nearly twice a many concepts in their maps as students in cluster 1. Similar to cluster 1, less than 9% of each grade level is represented in cluster 2.

Cluster 3—Three concepts, "atmosphere", "respiration", and "density of air" were not used by any students in this group, and another five concepts were each used by only one student. Only three concepts, "water", "melts", and "freezes" were used by at least seventy-five percent of this group of 21 students. The average number of concepts used is about three more than cluster 1, and about the same as cluster 4. About eighteen of the thirty concepts provided have similar occurrences in cluster 3 and in cluster 4. Less than 7% of each grade level is represented in this cluster.

Cluster 4—Although Clusters 3 and 4 have the nearly the same average number of concepts, they differ both in concepts not used and in most commonly used concepts. One concept, "infiltrates", was not used in any map in this cluster, and three concepts were each used by only one student. The concepts, "water", "water vapor", and "lakes and rivers" were used by at least seventy-four percent of the 38 students in this group. The concept water was used by 97% of the students in this cluster. The membership of this cluster ranges between 11.3% and 7% of each grade level.

Cluster 5— All 57 students in this cluster used the concepts "water", "lakes and rivers", "snow", and "rain", and all but one student included the concepts "land or soil", "cloud", and "ice". Twenty-two concepts were each used by at least seventy-four percent of the students. Cluster 5 shows the highest average at nearly 84% for similarity in concepts selected, and a dramatic increase to an average of 23 concepts used. About twelve of the thirty concepts provided have nearly the same occurrence in clusters 5 and 7. Twenty percent of all twelfth grade students are included in this cluster, 10.5% of ninth grade students, and 13.3% of sixth grade students.

Cluster 6—Ten concepts were used by all 33 students in this cluster: "water", "ground water", "precipitation", "tiny droplets", "invisible", "visible", "cloud", "snow", "fog", and "atmospheric pressure". The lowest percentage occurrence for any concept for this cluster was 55%. This cluster has the highest average of 27 concepts per map, and there is about 83% agreement overall in concepts used. About fourteen concepts of the thirty concepts provided have about the same occurrences in clusters 5 and 6. Nearly 17% of all twelfth grade students in the study, 12.3% of the ninth grade students, and only 3% of the sixth grade students are represented in this cluster.

Cluster 7—Only one concept, "rain", was used by all 63 students; however, two additional concepts, "water" and "snow", were used by 98% of the students. Eleven concepts were used by at least seventy-five percent of the students in this cluster. The average number of concepts used drops for this cluster to about 18 concepts, but there is a better than 60% similarity on average for concepts used in these maps. Only eight of the concepts have about the same occurrence in clusters 6 and 7. About fifteen concepts have similar occurrences in clusters 7 and 8. This cluster includes 18.6% of all twelfth grade students, twenty percent of all ninth, and 13.8% of all sixth grade students in the study.

Cluster 8—Two concepts, "water" and "rain", were used by all 35 students in this cluster, followed by three concepts, "water vapor", "lakes and rivers", and "cloud" used by all but one student. Four concepts were not used at all: "respiration", "combustion", "infiltrates", and "atmospheric pressure"; and three more concepts, "transpiration", "separate molecules", and "density of air" were each used by only one student. Ten concepts were each used by at least seventy-five percent of the students in this cluster. Cluster 8 is closer to Cluster 2 in average number of concepts used, but this cluster has higher within cluster agreement in concepts used at 63.6% overall similarity. Only 4.2% of all twelfth grade students are represented in this cluster, 10.5% of ninth grade students, and 11.8% of the sixth grade students are included.

Cluster 9—The largest cluster with 74 members, Cluster 9 is similar to Clusters 2 and 8 in average number of concepts used. The percentage occurrence for the concepts is quite different from cluster 2 and more similar to cluster 8. One concept, "combustion", was not used by any student in the cluster, as was true of cluster 1 and cluster 8. Two concepts, "infiltrates" and "atmospheric pressure" were used each by only one student. Ten concepts were each used by at least seventy-five percent of the students. Three concepts, "water", "ice" and "rain" were used by 97% of the students in this cluster, the highest occurrence for any concepts in this group. Eleven percent of the twelfth grade students are represented in this cluster, 17.5% of the ninth grade students, and twenty-five percent of the sixth grade students.

Discriminating power of specific concepts.

Among the nine clusters, the observed range of percent occurrence of each concept is evidence of the discriminating power of the concept. The set of thirty concepts provided for the mapping task shows between the clusters considerable variance in usage. A wide range for percentage occurrence establishes the usefulness of specific concepts as discriminators. For example, atmospheric pressure has a range of 100%: the concept atmospheric pressure was used by every student in cluster 6, and no student in cluster 8. Table F1 in Appendix F ranks concepts by range of percentage occurrence of each concept within each of the nine same-concept clusters. The first fourteen concepts in Table F1 have a range of occurrence of eighty percentage points or more among the clusters. Water is the concept most uniformly applied, and even water has a range of 12% occurrence between clusters. Evaporation, the second most commonly used concept spans a 42% range of occurrence across clusters.

This evidence supports the assertion that when students are allowed to select for their concept maps a subset from the provided list of concepts, concept maps may be discriminated on the basis of concepts used.

Summary of the analysis of concepts selected.

In summary, the first level of analysis shows that concept maps can be discriminated on the basis of number of concepts included and which concepts were used.

Cluster analysis groups concept maps by similarity in concepts selected. Inspection of the clusters shows that the concepts provided in language-constrained concept mapping are selected differently by students, and when students are not required to use all concepts in the list provided, the concepts selected may be used to differentiate groups of students. The percent occurrence of concepts in maps of each cluster shows a considerable range. Some concepts were not used by any students in a given cluster while other concepts were used by all students in some clusters.

The fact that similar concepts were used does not provide information about how students perceived the concepts to be related. The next section proceeds to the second level of analysis which examines the connections between the concepts. The analysis begins with a comparison of the number of concept pairs, followed by an analysis of specific concepts-connected. Since all clusters of similar concept sets consisted of students from all three grade levels, all 378 maps were compared for similarities in concepts-connected. Clusters of similar concept sets were not preserved for this analysis since the fact that the concepts were present in the cluster does not imply that they would be connected in the same way. The overlap in concepts across the nine clusters in the first level of analysis hints that cluster membership may rearrange when the connections between concepts is added to the comparison.

Analysis of Concepts-connected

The number of concept pairs identified in each map ranged from a minimum of five to a maximum of forty-four with an average of 16.8 relations per concept map. The pattern of concept pairs per map follows a normal distribution as shown in Figure 3.7.

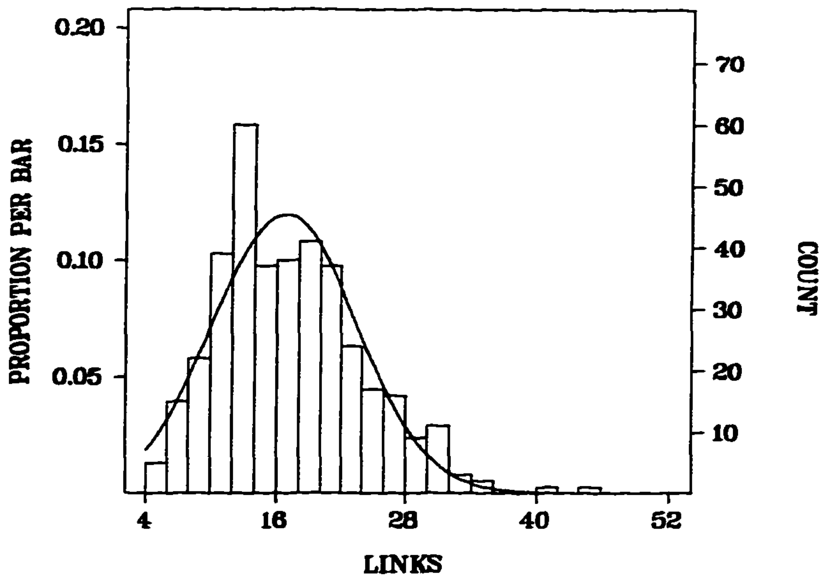

Figure 3.7 A histogram of the number of concept pairs in maps of students in grades six, nine, and twelve

Number of concept pairs by grade level

The percentage of students connecting less than ten concept pairs in their maps were 8.5% of twelfth grade students, 7% of ninth grade students, and 13.8% of sixth grade students. At the other end of the spectrum, one ninth grade student had the overall high of forty-four concept pairs. Twelve twelfth grade students had between thirty and forty concept pairs in their maps. Three sixth grade students had between thirty and thirty-two concept pairs, three ninth grade students had thirty or more concept pairs. A comparison of concept pairs by grade level is shown in Table 3.13.

Table 3.13

Average Number of Concept Pairs Used by Students in Grades 6, 9 and 12.

	Grade 6	Grade 9	Grade 12
Average	15.2	17.1	19.4
Confidence	0.79	1.87	1.26

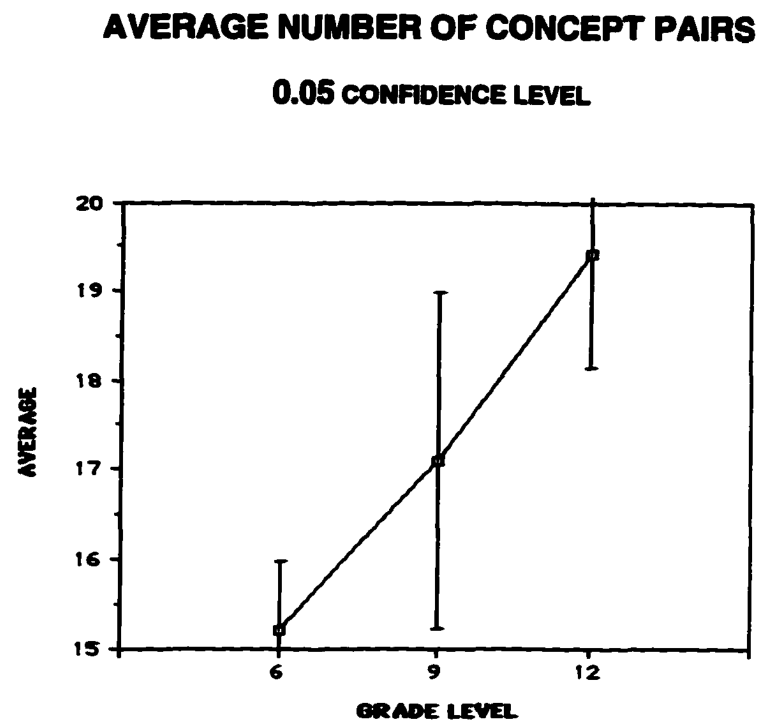

Figure 3.8. Graph of the average number of concept pairs used by students in grades 6, 9 and 12 showing the interval for a confidence level of 0.05.

The graph in Figure 3.8 plots the average numbers of concept pairs for each grade level shown in Table 3.13 and illustrates the variance at a confidence level of 0.05. As was true for the number of concepts used, a significant difference is found between the number of concept pairs used by sixth and twelfth grade students, but no significant difference when ninth grade students are compared to sixth and twelfth grade students for number of concept pairs used in maps.

Analysis of specific concept pairs selected.

There were 435 possible combinations of concept pairs. Three hundred sixty two different concept pairs were identified in this set of maps, ignoring differences in linking terms used to connect these concepts. A count for each grade level of different pairs of concepts-connected, disregarding choice of linking phrase or directionality of the relation shows a total of 303 concept pairs matched by twelfth grade students, 207 concept pairs matched by ninth grade students, and 298 concept pairs matched by sixth grade students. See Table 3.14.

Table 3.14

Frequency of Concept Pairs by Percentage Occurrence in Maps of Students in Grades 6, 9 and 12.

Break Points	Concept Pairs Used by		
%	12	9	6
0	132	228	137
19.9	283	182	281
24.9	8	10	1
29.9	2	9	6
34.9	4	1	3
44.9	3	2	5
49.9	2	1	2
50+	1	2	0
Total Pairs	303	207	298

Few concept pairs were selected by more than 30% of all students at a given grade level. For the twelfth grade, twenty concept pairs were used by at least 20% of the students, twenty-five concept pairs were used by at least 20% of the ninth grade students, and seventeen concept pairs were used by at least 20% of the sixth grade students. Most concept pairs were used by less than 20% of the students at the grade level, and a large number of concept pairs were connected by as few as one or two students at the grade level. The relatively large pool of concept pairs connected by students at each grade level together with the limited number of concept pairs found in each map predict differences when comparing student maps. The variety and uniqueness of student concept maps, even when built from the same structural elements, echoes the uniqueness of freely drawn maps and supports the use of a constrained mapping technique to get at student understanding of a domain.

Percentage occurrence for concept pairs by grade level.

This data indicates considerable variance in the percent occurrence of each concept pair at each grade level. This analysis shows that there are some concept pairs common to many maps, and these are usually combined with concept pairs found in only a few concept maps. A list of the most commonly occurring concept pairs are listed in Appendix D with the percent occurrence for each grade level and the rank order of occurrence for each grade level. Given this observation, when student maps are compared for similarities in concepts-connected, will clusters be found that are comprised of similar maps from all grade levels? The next step in the analysis will answer that question.

Analysis of similar concepts-connected.

All 378 student maps are compared with one another to see if groups of students connected concepts in the same way. To prepare the data set for the analysis, the list of triads found in each student map is processed to eliminate the codes for the linking phrases, leaving a list of dyads representing concept pairs only. Directionality of each relation is removed by ordering concepts in the dyad from lowest to highest and eliminating any duplicates that may have been generated by bi-directional links between two concepts. These reduced lists are then compared for each pair of maps, calculating the ratio of the intersection to the union of concepts-connected in the two maps. To give a simple example, one map represents the concept pairs 1—2, 2—5, 2—9 and another map represents the concept pairs 1—2, 2—3, and 2—5. The intersection or common pairs are 1—2 and 2—5, or a set of 2 pairs in common. The union or set of all pairs represented in the two maps is a set of 4 pairs: 1—2, 2—3, 2—5, 2—9. The similarity ratio for these two maps would be 2/4 or 50% similarity. Most similarity ratios in this analysis fall below the fifty percent margin for concept pairs matched in the two concept maps compared.

Description of cluster analysis for concepts-connected.

As in level one analysis for concepts selected, the similarity ratios are subjected to cluster analysis to determine the number of groups and group membership. The steps in this cluster analysis parallel those of the prior analysis. The triangular matrix of similarity ratios for concepts-connected in all 378 student maps is converted to a distance matrix (1-x) and imported into SPSS. The data is identified in cluster analysis as a hierarchical distance matrix and Wards' Method using Euclidean distance is applied. The cluster analysis for similarity in concepts-connected produced thirty-three clusters at the first level of hierarchy. As this is considered to be too many clusters to compare meaningfully and expediently, fifteen larger clusters that merged at the second level were identified; further mergers at the third level reduced the number of clusters to twelve, and at the fourth level of hierarchy, the number of clusters reduced to seven. The characteristics of these seven clusters of maps are next examined to see whether the analysis of similarities in concepts-connected discriminates concept maps.

The composition of similar-concepts-connected clusters of maps.

The seven clusters of concept maps are compared in Table 3.15 for size and grade level membership. Clusters range in size from seventy-two to twenty-seven members. All cluster memberships span all three grade levels. Since the number of participants at the respective grade levels was unequal, the percentage of the grade level represented in the cluster is also noted. Cluster 7 is unusual in that only one ninth grade map is a member of that cluster. Clusters 1, 4 and 7 have a very high representation of sixth grade maps.

Cluster 1 has the highest percentage of twelfth grade maps. The remaining twelfth grade maps are distributed almost equally among the other clusters with the exception of cluster 3 which has a lower representation of twelfth grade maps. The highest numbers of ninth grade maps are found in clusters 4 and 5.

Table 3.15

Cluster Membership Distribution by Grade Level Showing Percentage of All Grade Level Participants in Clusters if Same-Concepts-Connected Ordered by Increasing Numbers of Concept Pairs

	Grade				Percent of Grade		
Cluster	6	9	12	Total	6	9	12
3	14	5	8	27	6.9	8.8	6.8
1	40	7	25	72	19.7	12.2	21.2
4	46	14	17	77	22.7	24.6	14.4
2	27	9	16	52	13.3	15.7	13.6
5	27	16	17	60	13.3	28.0	14.4
7	40	1	17	58	19.7	1.7	14.4
6	9	5	18	32	4.4	8.8	15.2
Totals	203	57	118	378	100.0	100.0	100.0

Distinguishing characteristics of similar-concepts-connected clusters of maps.

How do maps in one cluster differ from those in another cluster? The next section examines a few characteristics such as average number of concept pairs, number of concept pairs represented in at least 30% of all maps in the cluster, and concepts most linked to other concepts based on the composite of all concept maps in the cluster. The average similarity ratio for within-cluster similarity is reported for each cluster.

Although the average number of concept pairs in each map of the cluster is unrelated to similarities in concept pairs, it is a characteristic of some interest. One student may have connected only five concept pairs, but those five connections may be a perfect sub-set of another concept map having more than twenty concept pairs linked. There is a good chance that students who connected few concept pairs connected different concept pairs; however, some of the concept pairs may be the same as those connected by a student connecting many pairs. Therefore, clusters may be expected to have a wide range in a count of concept pairs per map as evidenced in Table 3.16.

Table 3.16

Cluster Size, Average, Median and Mode for the Number of Concept Pairs in Clusters of Maps with Similar Concepts-connected

		Number of Concept Pairs				
Cluster	Size	Average	Median	Mode	St. Dev	Confid
3	27	12.9	13	13	3.12	1.18
1	72	14.9	13	10	7.12	1.64
4	77	14.9	13	12	5.52	1.23
2	52	16.7	16	13	7.07	1.92
5	60	18.1	17	16	6.08	1.54
7	58	18.3	18	20	4.52	1.16
6	32	22.0	20.5	14	8.48	2.94

Cluster 5, 6 and 7 have the highest average numbers of relations. The mode for cluster 6 is lower than might be expected as that cluster has the highest average and median for number of concept pairs per map. The mode for cluster 1 is the lowest at ten concept pairs per map. Clusters 1, 3, and 4 have the lowest average numbers of concept pairs. Cluster 1 is comprised of about 20% of all sixth and twelfth grade students. Cluster

4 consists of about 23-24% of all sixth and ninth grade students. Cluster 3 is comprised of less than 9% of each grade level. Cluster 6 has 15.2% of twelfth grade and 5-9% of sixth and ninth grade students. These differences can be seen graphically in Figure 3.9.

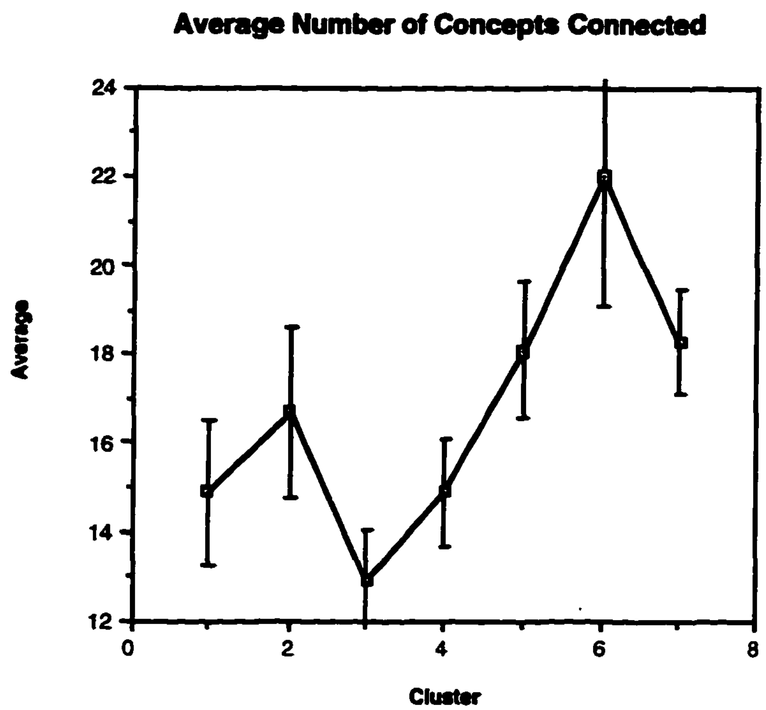

Figure 3.9. Graph of the average number of concept pairs in each of the seven clusters of concept maps grouped by similarity in concepts-connected. The graph shows the interval for a confidence level of 0.05.

There is a significant difference at the 0.05 confidence level between the average number of concept pairs per map in clusters 5, 6, 7 and those in clusters 1, 3, and 4. There is also a significant difference between the average number of concept pairs in cluster 7 and clusters 1 and 2,; and there is a significant difference between the average number of concept pairs between cluster 2 and cluster 3.

The number of concept pairs connected in each map may be indicative of the student's scope of understanding. For example, the student maps in cluster six which has the highest average number of concept pairs may be expected to show better understanding of the domain than maps in cluster 3 which has the lowest average number of concept pairs. The specific concepts-connected would be more indicative of the level of understanding represented by the maps of each cluster, but how close is the agreement between the maps of each cluster? If each student connected only a few concept pairs, there would undoubtedly be some similarities and many differences between the pairs selected by the students in each cluster. To get an idea of the variation of concept pairs in each cluster, the total number of different concept pairs that were represented in at least two concept maps in that cluster were compared with the number of different concept pairs that appeared in at least twenty percent of the maps in the cluster. Counts for each of the clusters are found in Table 3.17.

Table 3.17

A Count of Unique Concept Pairs Identified within Clusters of Maps with Similar Concepts-connected

Cluster	Concept Pairs		
	Total	in at least 20% of Maps	Ratio
3	45	15	0.3333
6	104	28	0.2692
7	108	26	0.2407
5	129	23	0.1783
2	140	16	0.1143
4	145	18	0.1241
1	192	6	0.0313

The greater the diversity in concept pairs identified within a cluster of concept maps, the less similarity is expected between the maps. The ratio of the total pairs to common pairs in Table 3.16 leads to the prediction that cluster 1 will have a very low average similarity ratio. Many of the pairs of concept maps compared in Cluster 1 could have similarity ratios of zero, or no concept pairs common to both of them. Cluster 3 is expected to have a high average similarity ratio since there appears to be closer agreement on the concept pairs selected with only 45 different pairs each represented in at least two maps. In the next step of the analysis, the maps of each cluster are compared for similarities in concepts-connected. The average similarity ratios within clusters are reported in Table 3.18.

Table 3.18

Similarity Ratios Comparing Concept Pairs within Clusters of Maps with Similar Concepts-connected

	Similarity Ratios			
Cluster	Average	Maximum	Minimum	Standard Deviation
3	0.2398	0.500	0.091	0.0815
7	0.1847	0.591	0.026	0.0688
6	0.1817	0.385	0.056	0.0609
5	0.1399	0.462	0	0.0595
4	0.1075	0.438	0	0.0622
2	0.0912	0.500	0	0.0567
1	0.0434	0.538	0	0.0458

As predicted, cluster 1 shows a very low average similarity measure, and many of the pairs of concept maps had no concept pairs in common. Clusters 2 and 4 appeared to be more similar in numbers of concept pairs and in pairs appearing in at least twenty percent of the maps of the cluster; they are also very close in their average similarity ratios. Cluster 3 has the highest average similarity ratio for concepts-connected. Cluster 3 had the lowest number of unique concept pairs and the lowest number of concept pairs per map.

Of greater interest is specifically which concepts are connected in these maps. How different are the concept pairs represented in each of the clusters? When the same concept pairs are represented, how do the percent occurrences for these concept pairs compare? To see whether the analysis discriminates between maps, characteristics of each of the seven clusters are described in the next section.

Cluster 1—This is one of the largest clusters with seventy-two members. In a composite of all the maps in this cluster, all concepts provided are represented. There are an average of 14.9 relations per map, but there is wide assortment of concept pairs represented. No concept pair was selected by thirty percent or more of the students in this cluster. The highest percentage occurrence is 29.2% for the link between "water" and "evaporation". This cluster of maps is a cluster of maps that are more idiosyncratic and do not find matches to maps in other clusters. They do not even find good matches within this cluster. Cluster 1 consists of about 20% of all sixth and twelfth grade students, and about 12% of the ninth grade students.

Cluster 2—Each of the thirty concepts provided is represented in at least one map of this fifty-two member cluster. The average number of concept pairs per map is a bit higher than cluster 1 with 16.7 relations per map. There is considerably better agreement in the choice of concepts linked. Seven concept pairs occur in more than thirty percent of the maps in this cluster. "Water" is joined to "lakes and rivers" in 55.8% of the maps, "water vapor —cloud" in 50%, and "water—water vapor" in 48%, and "ice—freezes" in 46%. Maps in cluster 2 have some pairs in common with cluster 3 and with cluster 7, but are largely missing the process concepts found in cluster 7 maps and the links to "land or soil" and to precipitation as found in cluster 3 and cluster 7 maps. Cluster 2 consists of about 13% of all sixth and twelfth grade students and about 16% of the ninth grade students.

Cluster 3—The smallest cluster with only twenty-seven members, this cluster is remarkable in the absence from all maps of several concepts. No member of this cluster included the concepts "respiration", "infiltrates", "density of air", or "atmospheric pressure", and only one member included "combustion", "transpiration", and "separate molecules". There are an average of 12.9 relations per map, the lowest for the seven clusters, yet there is good agreement in the selection of some concept pairs. Of the forty-five concept pairs linked by at least two students in this cluster, thirteen of the concept pairs occur in at least 30% of the maps. Every member of this cluster connected "water—lakes and rivers", and 89% linked "water—water vapor" and "water—ice". The inclusion of "ground water" and "precipitation" and three concept pairs including "water vapor" distinguish cluster 3 from cluster 4. Cluster 3 consists of less than 9% of each of the grade levels.

Cluster 4—The largest group, this cluster consists of seventy-seven maps. All thirty concepts provided are represented in the composite map of this cluster. The average number of relations per map is 14.6. Only eight concept pairs are joined by at least thirty percent of the students in this cluster. "Water" is linked to "rain" in 63.6% of the maps in this cluster, and "water—ice" in 62%, followed by "water—lakes and rivers" in 55.8% of the maps. Although clusters 3 and 4 have several concept pairs in common with cluster 5, the inclusion of the connection between "rain—tiny droplets" further distinguishes them from cluster 5. Cluster 4 consists of 23% of the sixth grade students, 25% of the ninth grade students, and 14% of the twelfth grade students.

Cluster 5—This sixty member cluster has an average of 18.1 relations per map. A total of 129 different concept pairs were each connected by at least two students in this cluster, but only ten concept pairs were connected by at least thirty percent of the students in this cluster. "Precipitation" and "rain" were linked in 93.3% of the maps while 68% show "precipitation—snow" and "water—lakes and rivers". Fifty-two percent connected "water—water vapor". The inclusion of two concept pairs with "cloud" and two pairs with precipitation separates cluster 5 from clusters 3 and 4. Cluster 5 consists of about 13% of the sixth grade students, 28% of the ninth grade students, and 14% of the twelfth grade students.

Cluster 6—This small cluster of thirty-two members shows good agreement in concept pairs selected. Fifteen specific concept pairs are common to at least thirty percent of the maps. The higher percentage occurrence of the four concept pairs "water vapor—condenses", "lakes-rivers—run off", "frost—freezes", and "cloud—fog" set cluster 6 apart from all other clusters. In addition, every map in this cluster contains the link "ice—freezes", and 78.1% include the pair "water—freezes" and the pair "rain—precipitation". The concept "water" is linked to "evaporation" in 68.8% of the maps while "melts" is linked to "snow" and to "water" equally in 62.5% of the maps. The inclusion of the processes "melts", "freezes", and "evaporation" distinguishes maps of cluster 6 and 7 from those in clusters 3, 4, and 5. Cluster 6 consists of about 4% of the sixth grade students, 8.8% of the ninth grade students, and 15.2% of the twelfth grade students.

Cluster 7—This cluster holds fifty-eight members with an average of 18.3 relations per map. There is broad variation in the connections formed. One hundred and eight different concept pairs were each used by at least two students in the cluster. Sixteen concept pairs occur in at least thirty percent of the maps. The two most commonly found concept pairs are "ice—melts" and "ice—freezes", found in 79.3% and 74.1% of the maps in this cluster. The "water—water vapor" link is identified in 68.9% of the maps. The most distinguishing links are the connection between "cloud—rain", which is common to cluster 2, but a much higher percent occurrence in cluster 7. Other concept pairs that set cluster 7 apart are "land-soil—rain", "tiny-droplets—rain", and "ice—melts" that occur at a higher percent in cluster 7 than in other clusters. Cluster 7 consists of 19.7% of the sixth grade students, 2% of the ninth grade students, and 14% of the twelfth grade students.

Discriminating power of specific concept pairs.

Although this discussion shows that each cluster has recognizable and distinguishing characteristics, it also substantiates that certain concept pairs discriminate between clusters. The discriminating power of concept pairs may be visualized more clearly by listing in Table 3.19 of all concept pairs having at least thirty percent occurrence within each of the seven clusters.

Table 3.19

Percentage Occurrence of Discriminating Concept Pairs within Clusters of Maps with Similar Concepts-connected

	Clusters						
	1	2	3	4	5	6	7
water vapor condenses						46.8	
lakes rivers run off						31.1	
lakes rivers rain				30			
cloud fog						43.8	
freezes frost						31.1	
precipitation cloud					36.7	37.5	
precipitation snow					68	56.2	
water groundwater			37		41.6		
water precipitation			41		35		
water snow			44	41.6			
water ice			89	62			
water melts						62.5	34.5
water freezes						78.1	67.2

Table 3.19 (continued)

Percentage Occurrence of Discriminating Concept Pairs within Clusters of Maps with Similar Concepts-connected

	Clusters						
	1	2	3	4	5	6	7
snow melts	23.6					31.1	
cloud rain		38					53.4
snow freezes	22.2						32.8
water evaporation	29.1					68.8	41.4
land or soil rain			29.6		30		48.3
tiny droplets rain			33	31			58.6
water rain			66	63.6			34.5
ice melts		36.5				62.5	79.3
ice freezes		46				100	74.1
water vapor evaporation		40.3	44		56	59.3	48.3
water vapor invisible	20.8		56			40.6	36.2
water vapor cloud		50.0	33		45		37.9
water lakes rivers		55.8	100	55.8	68		60.3
precipitation rain			56	32	93.3	78.1	53.4
water water vapor	20.8	48	89	40	52		69
Total Pairs >=30%	0	7	13	8	10	15	16

Twenty-two of the concept pairs in Table 3.19 have thirty percent occurrence or better in one to three clusters. These pairs are very useful in discriminating between clusters. Even the six concept pairs that are found in four or five clusters at the thirty percent or higher occurrence can discriminate between clusters since there is variation in the percent occurrence.

Summary of concepts-connected analysis.

This analysis calculated similarity ratios for the characteristic concepts-connected between every pair in the entire group of 378 maps. Cluster analysis was then applied to group the maps on the basis of their similarity ratios. Since, for this analysis, the lowest level of hierarchy in the cluster analysis consisted of too many clusters to efficiently consider, larger clusters at the fourth level of hierarchy were used. Even at the fourth level of hierarchy differences are identified in the concept pairs most predominately used in each cluster. Therefore this study concludes that the method of analysis can discriminate between concept maps on the basis of concepts-connected.

Analysis for Similarity of Concepts-Connected and Linking Phrases Selected

The complete analysis design calls for similarity measures comparing concept maps in layers of increasing similarity based on the elements of the construct: concepts used, concepts-connected, linking phrases, and directionality. To this point the research has compared the concepts used and concepts-connected. The relatively large size of the concept set provided, the number of linking phrases, along with the option to use only some of the concepts contributed to the low similarity measures even at these first two levels of comparison for concepts used and concepts-connected. When linking phrases are added to the comparison, variation increases and similarity measures become too low for useful analysis. The comparison of maps based on linking phrases and directionality is not pursued in depth in this dissertation. However, for clusters of the same concepts-connected, a comparison of linking phrases used may help to interpret the viability of the links selected. For example, cluster 3 which had the highest average similarity, 0.24, for concepts-connected, had an average similarity of only 0.095 when linking phrases were included in the comparison. The highest similarity between two maps in cluster 3 was 0.4 or 40% for similarity in concepts-connected and linking phrases used. The reason for the low similarity ratios becomes apparent when just one relation in the maps of cluster 3 is examined. Twenty-four of the twenty-seven students in this cluster connected water to water vapor. Seven students chose the simple linking phrase "is/are", nine students selected "produces/forms", two students used "is a cause of", four chose "rises into" , one student used "into", and another used "falls on". Similar variation in selection of linking phrases may be expected for other concept pairs, and the similarity ratios will be correspondingly low.

Analysis for Similarity of Concepts-Connected, Linking Phrases Selected, and Directionality of Relations

When directionality of the relations deepens the level of comparison, the resulting similarity measures are expectedly lower. For this data set, the very low similarity measures provided no further useful information to the analysis and are not reported.

Since the similarity ratios in this study tended to be well under sixty percent similarity for maps compared, other analysis schemes were developed to boost the power of the tool to discriminate between maps. Some of those efforts will be described briefly in the next section.

Other Analysis Schemes Used

Students were not required to use all concepts provided and both of the number of concepts and the set of concepts used varied greatly among the maps. Instead of focusing attention on all thirty concepts provided, maps that have used the same set of concepts can be isolated. To accomplish this, the concepts used are listed for each map and sorted by percent occurrence over all maps.

Same ten concepts used.

A sort of the 378 concept maps by concepts used suggests a cutoff at the ten concepts of highest occurrence which reduces the data set to 99 maps. The data set includes 50 maps constructed by grade twelve students, 16 maps of grade nine students, and 33 maps of grade six students. The subsequent analysis is expected to provide more focused information about how students connected these ten concepts.

Test point.

Another analysis technique includes in the data set a map designed by the researcher that consists of a small focused subset of links of interest. A modified calculation of similarity ratios that tests only the concepts of interest when comparing each map to the test point establishes the relative likeness of each student map to the test map. When the similarity data is imported into SPSS for multidimensional scaling analysis, the reaction of the student maps to the test map can be visualized. Student maps will cluster closer to the test map or test point if they are similar, and position farther from the test point if dissimilar. This method would be useful for probing group understanding of a specific subset of conceptual relationships within the maps. More than one test point or test map could be used simultaneously, particularly if there are two or more distinct and opposing patterns expected to emerge in different maps as may be possible with alternative conceptions. One test map consisting of accepted concept pairs and another consisting of alternative concept pairs may be expected to polarize the concept maps when multidimensional scaling is applied to similarity ratios for concepts-connected.

Other analyses were attempted and were considered ineffective in discriminating between concept maps. These attempts will be briefly described in the next section.

Other Analysis Schemes Not Used

Twenty or more relations.

The initial similarity calculations for concept pairs reveals lower than expected values. This is attributed in part to the fact that participants were not required to use all concepts, but could use as many or as few as they chose. The "twenty relations" approach is based on the hypothesis that a data set in which each map has a larger number of relations might include more common relations between the maps. To find a data set exhibiting greater similarities among maps, only those concept maps having at least twenty relations are included in the analysis. Since those twenty relations still include the full range of concepts and a very broad range of concept pairs, the similarity measures do not significantly improve with this restriction.

Two-away similarity measures.

The assumption that one student may directly join a concept pair while another student places an intermediate concept between the two concepts drives this method of analysis. For example, one student may link "water—ice" while another links "water—freezes" and "ice—freezes". At the level of two-away, both students have linked water to ice and are therefore considered similar.

In this analysis, all one-away and two-away concept pairs are considered for every map, considerably swelling each map's list of concept pairs. Similarity measures, however, divide the number of matched pairs by the total number of different pairs in the two maps compared. The flaw in the approach is that although the number of matched pairs increases, the denominator of total different pairs increases dramatically with the result that the similarity ratio is very low. Therefore, the method of two-away analysis, by this method of comparison, is not found to be more fruitful than the simple one-away analysis used in this study.

Summary

Study 3 tests whether a language-constrained computer-assisted concept mapping task can be used to discriminate students on their knowledge of a domain. The following evidence supports the use of language-constrained computer-assisted concept mapping to discriminate students on their understanding of the domain.

A significant difference is found between grade six and grade twelve students in the number of concepts used and number of concept pairs formed. No significant difference is found between grade nine students and grade six or grade twelve students for concepts used or concept pairs formed.

Cluster analysis based on similarity ratios for concepts used produces nine groups of maps which can be shown to have unique patterns of concept occurrence. These clusters also differ in the average number of concepts per map. All similar-concepts clusters included maps of students of each grade level, but in varying percentages.

An analysis of concepts-connected shows a significant difference between sixth and twelfth grade students for numbers of concept pairs represented, but no significant difference between ninth grade students and sixth or twelfth grade students. Cluster analysis based on similarity ratios for concepts-connected produces seven groups of maps which have unique patterns of concept-pair occurrence. These cluster differ in the average number of concept pairs per map, differ in the number of unique concept pairs identified in the collective maps of the cluster, and differ in the number of connections to core concepts. The clusters also differ in the composition of the membership or percentage of students of each grade level represented.

This analysis supports the ability of language-constrained computer-assisted concept mapping to produce concept map data sets that can discriminate between maps on the basis of two fundamental components of concept maps: concepts used and concepts-connected.

In summary, Study 3 shows that the application of similarity measures to a set of concept maps for concepts used and concepts-connected can discriminate between maps and establish clusters of similar maps that may be useful for the interpretation of shared student understandings, focusing not on the individual maps but rather on characteristics and patterns found in clusters of similar maps.

Although Study 3 dissects the maps into components of concepts used and concepts-connected, the analysis tools also aggregate the maps of each cluster to discover how, collectively, students in each cluster have linked these relationships together. In the next study, a more holistic view of the map clusters seeks evidence of map characteristics that may indicate levels of developing understanding.

Study 4: Evidence of Patterns of Expertise in Language Constrained Concept Maps

Overview

This study continues the analysis of data collected in Study 3. There are two parts to this study. The first part focuses on the global relationships between concepts using the seven clusters derived in study 3 from the analysis of similarities in concepts-connected. The maps for each cluster are aggregated into a composite map, and characteristics of the composite maps are then examined for evidence of developing understanding. Clusters of concept maps grouped by similarity in concepts-connected may differ in the scope of concepts represented as well as in the conceptual framework that organizes the ideas represented. For example, a progression of understanding may be revealed by the increasing structural complexity of the composite maps and expanded core framework. When these maps are organized around the same framework, a progression in similarity to the most complex map should be evident.

The second part of this study looks for evidence of increasing levels of understanding among grade levels. This evidence is sought two ways: 1) in the patterns of distribution of grade levels among the clusters of similar maps when these clusters have been ordered by increasing complexity; and 2) in a comparison of the three grade-level composite concept maps for the level of complexity, cohesiveness of ideas, and extent of the contiguous core knowledge represented.

Analysis

A ready means of visualizing the composite concept maps is found in the program KNOT-Mac. The input required in the program is a matrix format where each row of the matrix represents the concept from which the relation originates; each column in the matrix represents the concept to which the relation points. A set of thirty concepts is represented in a 30 x 30 adjacency matrix. Each relation is represented by a value of 1 at the matrix coordinates of the two concepts in the relation. To generate the adjacency matrix for the composite, a Hypercard stack was developed to translate each triad in the coded map list, e.g. 3 A 1, as from and to concepts and to add 1 at the locus of the coordinates. Information about linking phrases used to connect concepts is lost in this matrix transformation, but linking phrases are also disregarded in forming the original seven clusters. The original seven clusters also eliminate directionality of the links. To eliminate the directionality from the matrix, the square adjacency matrix was converted to a triangular matrix, summing the to-from and from-to relations between each pair of concepts.

The triangular adjacency matrix for each cluster was imported into KNOT-Mac to reconstitute the graphic representation of the composite concept map. The relative strength of each link between concepts varies directly with the number of students making the connection. Although all connections within the composite appear to be equal, the strong and weak connections or overall strength of the composite are not identified. All relations made by students in the cluster are not depicted since this would equally represent any connections made by just one student. The stronger connections made by a larger percentage of the students in each cluster are most important to understanding the commonalities in the way the group connects the ideas. Connections of greater strength can be visualized by adjusting the minimum weight variable in the preferences section of the matrix file.

The next section shows one way to obtain further detail of the group's shared understanding portrayed by each composite map.

Thin-Slicing a Composite Map

Slices of the composite concept map show connections over a scale of percentages or strength of relationships that may be useful in further assessing the level of students' shared understanding. Cluster 6 is used to illustrate the process here.

At least seventy-five percent of the students in cluster 6 connected three concept pairs: "water—freezes", "ice—freezes", and "rain—precipitation". At least fifty percent of the students connected six concept pairs, including a four concept cycle developed around the melting and freezing concepts. A sub-group of types of precipitation appears at the fifty percent level of agreement. The composite map of cluster 6 showing the concept pairs represented by at least fifty percent of the students is shown in Figure 3.10.

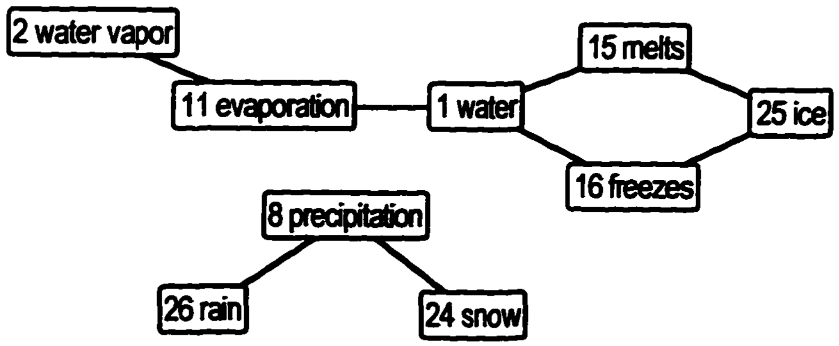

Figure 3.10. Composite concept map for Cluster 6 depicting relations constructed by at least fifty percent of the students. Numbers represent order in the concept set provided.

At the forty percent level of agreement, the two sub-groups remain separated. The concept "invisible" is connected to "water vapor", and the segment "cloud—fog" is added as another sub-group. Although these are simple additions, they indicate some depth of understanding, but a need to integrate subgroups of ideas remains. The composite map showing connections of at least a 40% level of agreement is shown in Figure 3.11.

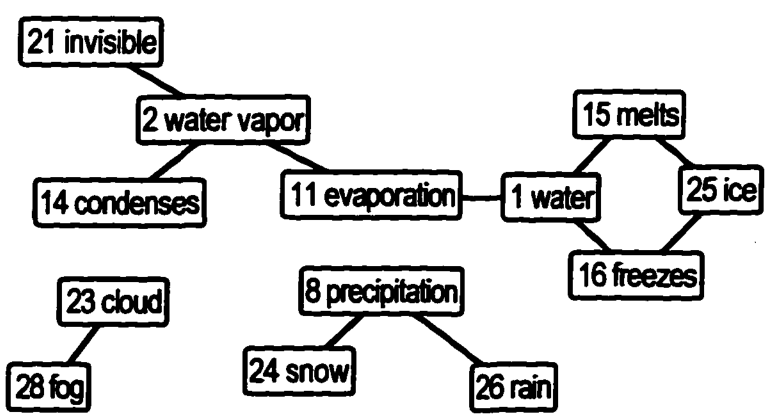

Figure 3.11. Composite concept map for Cluster 6 depicting relations constructed by at least forty percent of the students.

The thirty percent solution shows an increase in the structural complexity of the map. The two sub-groups are joined by a connection between "snow — melts" and "snow— freezes". A new sub-group consisting of the two concepts, "run-off —lakes and rivers" appears. The concept "cloud" is a major change at this level, bridging between "water vapor" and the concepts "rain", "precipitation", and "fog". The introduction of "cloud" also generates a new cyclic structure in the map. "Frost" is connected to "freezes" and "tiny droplets" are joined to "water vapor". See Figure 3.12.

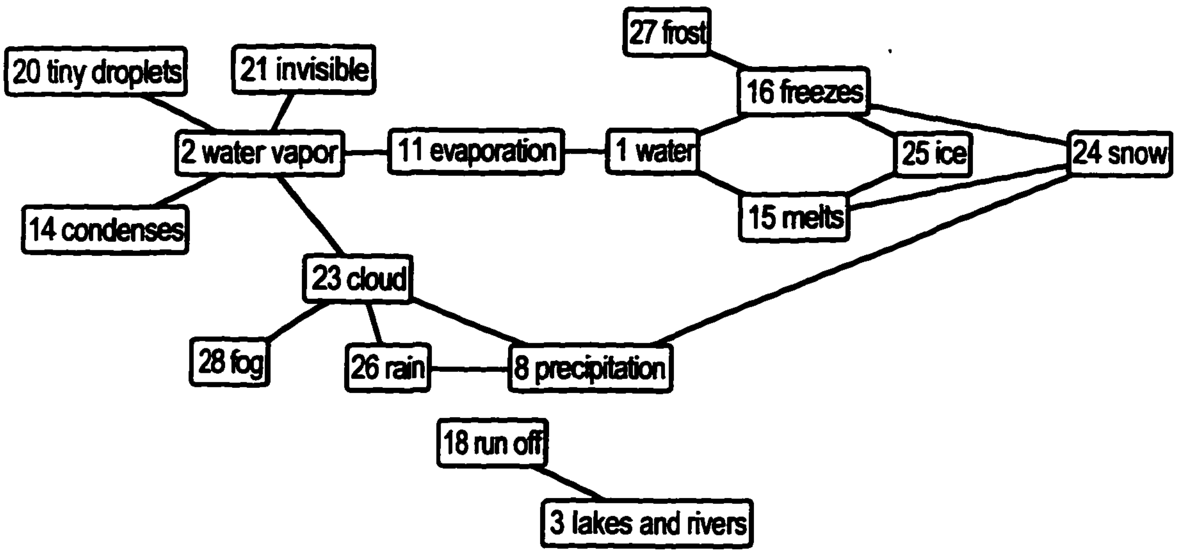

Figure 3.12. Composite concept map for Cluster 6 depicting relations constructed by at least thirty percent of the students. Numbers represent order in the concept set provided.

The depiction of the way that students see concepts-connected, and the ability to look at which concepts are most strongly connected provides the teacher with a tool to assess where students as a group are in their understanding of a domain and to design instruction around those common understandings as a bridge to deeper conceptualization of the relationships within the domain.

Part 1—Evidence for Developing Understanding Among Clusters of Maps

In this analysis, the decision of which percentage to use to compare the seven clusters is based on the fact that the percentage occurrence of few concept pairs in any cluster exceeded fifty percent; Cluster 1 had no relations at or above the thirty percent level, and few above the twenty-five percent level. To represent a layer of connectivity suitable to all clusters, the minimum weight selected for each cluster corresponds to twenty percent of the number of maps in the cluster. For example, n=77 for cluster 4, therefore twenty percent of 77 or 16 is the minimum count for connections displayed in the composite map. The minimum weight variable is calculated and entered for each cluster's matrix input file.

Composite maps that represent the twenty percent solution for each of the seven clusters are shown and critiqued in the next section. This analysis examines features such as the number of concepts in the composite map, branching characteristics, connectedness of concepts, core framework represented in each cluster, and fragmentation or insularity of concept pairs at the twenty percent level of occurrence. Missing concepts or relations may be noted as well as redundant or apparent alternative conceptions that may indicate levels of understanding. It should be noted that the direction of the links is eliminated here by summing the "to-from" and "from-to" pairs. The directionality represented in the composite map is a consequence of position in the triangular adjacency matrix and does not reflect the actual direction of links between concepts in the original maps.

Description of composite maps.

Cluster 1 appears to be a cluster of very idiosyncratic maps that bear little resemblance to one another or to maps in other clusters. The novel relationships depicted in these maps may represent alternative conceptions and/or a level of understanding not common to any of the other clusters. In other words, it is conceivable that this group of maps may contain the occasional map that indicates deeper understanding reflected in an unusual linkage, along side maps that show scattered and undeveloped ideas about how the concepts are related. The composite map of cluster 1, depicted at the twenty percent minimum strength, is shown in Figure 3.13. No cyclic relationships are represented. All relations are simple strands with minimal branching; only one concept, water, is connected by at least three links to other concepts.

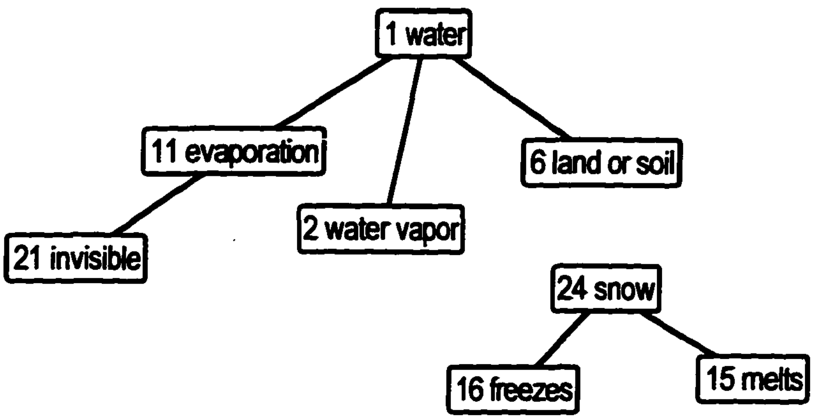

Figure 3.13. Composite concept map for Cluster 1 depicting relations constructed by at least twenty percent of the students. Numbers represent order in the concept set provided.

This composite for cluster 1 includes just seven concepts and only six relations. The core consists of five concepts along with a satellite group relating "freezes—snow—melts". All relations are viable, but the ideas are simple and undeveloped. No more than one level of hierarchy is shown, and branching is minimal. In cluster 1 there is minimal consensus on the relations between the concepts. Based on the evidence of the concept mapping task, this group does not share an extensive core framework of knowledge of the domain.

At least twenty percent of the students in cluster 2 agree on the connections between fourteen concepts. At this level of strength of connectivity there are three levels of hierarchy. "Cloud" is the most connected concept with links to five other concepts. "Tiny droplets" is cross-linked to "cloud" and "rain". The recognition that "fog" is related to "cloud" is included here. The processes "melts" and "freezes" are linked to "rain", "ice", and "snow". This indicates the emergence of a weather theme, while the inclusion of "lakes and rivers", "ground water", and "land or soil" indicate some understanding of the movement of water in the water cycle. The map for cluster 2 is shown in Figure 3.14.

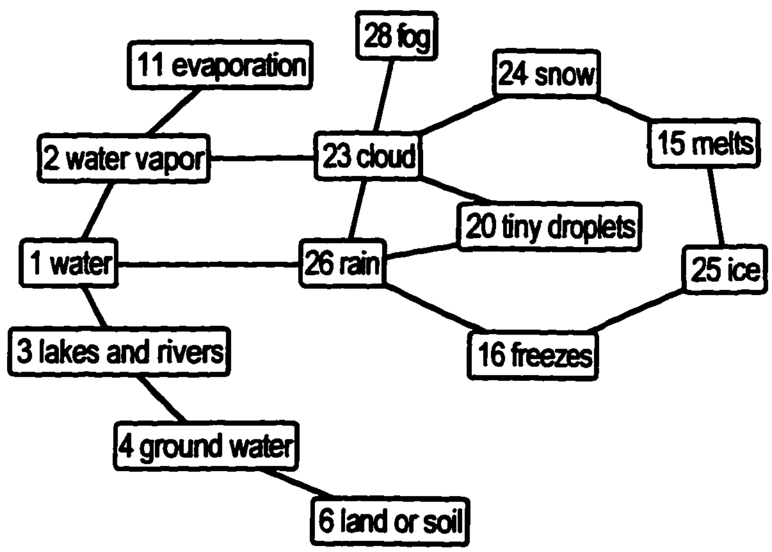

Figure 3.14. Composite concept map for Cluster 2 depicting relations constructed by at least twenty percent of the students. Numbers represent order in the concept set provided.

Note that for cluster 2, three concepts have three or more links to other concepts. Two cyclic patterns emerge, one with three concepts, and an adjacent cycle of six concepts.

The composite map at the twenty percent level for cluster 3 depicts sixteen relations between fourteen concepts as shown in Figure 3.15. "Water" is the most connected with links in a star configuration to eight other concepts. Two levels of hierarchy are represented. Two adjacent cyclic patterns, one a group of three concepts, the other a group of four concepts, share two concepts for a total of just five cyclic concepts.

Although the three concepts "groundwater", "lakes and rivers", and "land or soil" are included, they are not related to one another but link only to "rain" and "water". "Evaporation" links to "water vapor", but not to "cloud". "Ice" and "snow" are identified as forms of water, but the concepts of melting and freezing are absent. "Water vapor" is noted to be "invisible", and "water" "visible". A framework for weather or the water cycle is barely recognizable at the twenty percent level of Cluster 3.

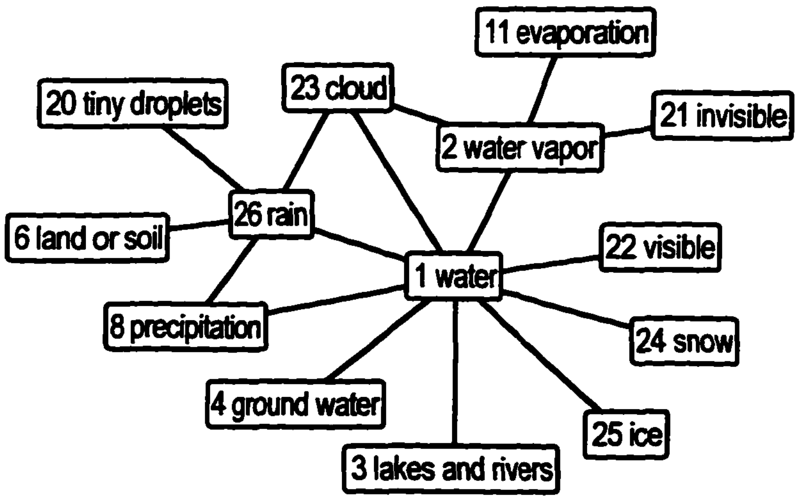

Figure 3.15. Composite concept map for Cluster 3 depicting relations constructed by at least twenty percent of the students. Numbers represent order in the concept set provided.

Cluster 4, shown in Figure 3.16, shows fifteen concepts in eighteen relations. Three concepts each have at least three connections to other concepts. Four cycles of three concepts each are noted, consisting of a total of eight concepts.

Cluster 4 is in several respects similar to Cluster 3. "Water" is the most connected concept with relations to eleven other concepts. "Rain" is linked to five other concepts, and "water vapor" to three. The process of "evaporation" links "water vapor" to "water", but terminates there. "Cloud" is linked to "water", but not to "water vapor". "Precipitation" or "rain" are not connected to "cloud", but "fog" is linked to both "cloud" and "water". Although the three concepts "land or soil", "lakes and rivers", and "ground water" are included, they are not linked to one another. The processes of melting and freezing are absent although "snow", "ice", and "frost" are linked to "water". No cohesive theme or process appears to be depicted at the twenty percent level. The Cluster 4 map depicts only two levels of hierarchy.

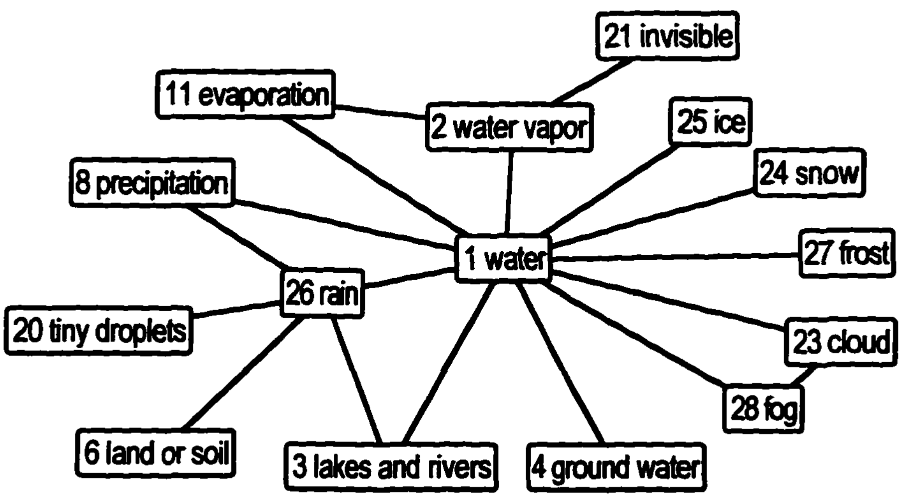

Figure 3.16. Composite concept map for Cluster 4 depicting relations constructed by at least twenty percent of the students. Numbers represent order in the concept set provided.

Relations at the twenty percent level in Cluster 5, shown in Figure 3.17, consist of seventeen concepts in twenty-one relations. Six concepts each have at least three connections to other concepts. Ten concepts form three cyclic patterns: two three-concept cycles, and one cycle of five concepts.

"Water vapor" is the most connected concept with links to six other concepts, followed by "water" and "precipitation" each with links to five other concepts, and "ice" and "rain" each with links to three other concepts. A cross-link to "rain" branches between the cluster of water vapor related concepts and the terrestrial strand of land/soil and ground water concepts. "Lakes and rivers" connects only to "water". "Ice", "rain", and "snow" are linked to "precipitation", but "snow" is not connected to the concept "freezes" or "melts" as is "ice", at least not at this level of connectivity. Overall, a more cohesive view of the hydrologic cycle is emerging in this cluster of maps.

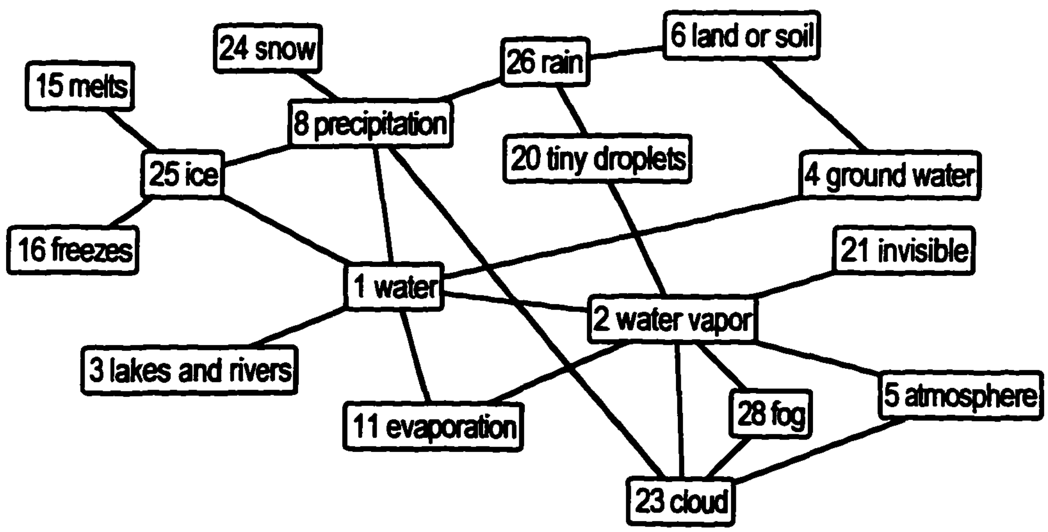

Figure 3.17. Composite concept map for Cluster 5 depicting relations constructed by at least twenty percent of the students. Numbers represent order in the concept set provided.

Cluster 6, shown in Figure 3.18, incorporates nineteen concepts in twenty five relations at the twenty percent level. Eleven of the concepts are broadly connected, having links to at least three other concepts. Concepts are cross-linked to form six cycles consisting of three concepts, and six cycles consisting of four or more concepts.

Ideas are more well developed, tying together "water", "evaporation", "water vapor", "condenses", "tiny droplets", and "cloud", leading to "precipitation". "Fog" is linked to "cloud". From "cloud", "rain" links to "land/soil", and "run off" is connected to "ground water" and "lakes and rivers". "Ice", "snow" and "frost" are linked to the processes of freezing and melting. "Water vapor" is indicated to be "invisible". This composite may be interpreted as having six to nine levels of hierarchy.

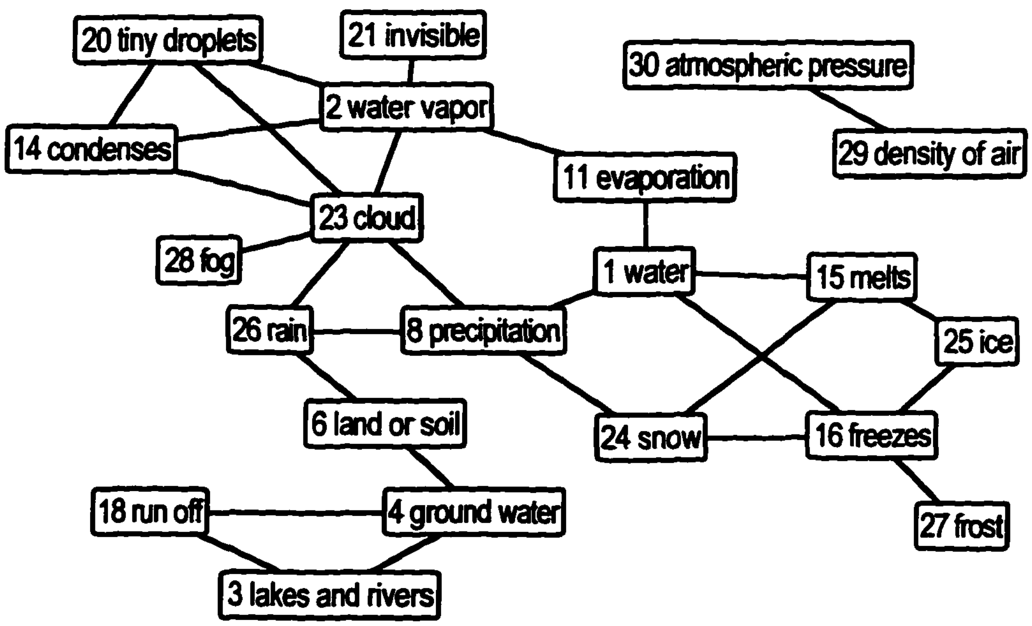

Figure 3.18. Composite concept map for Cluster 6 depicting relations constructed by at least twenty percent of the students. Numbers represent order in the concept set provided.

Cluster 7 incorporates eighteen concepts in twenty-two relations at the twenty percent level. Eight of the concepts are connected to at least three other concepts. One three-concept cycle is seen, and four cycles consisting of four or more concepts.

"Water" is linked to six other concepts, "freezes" and "water vapor" are each linked to four other concepts, "rain" to five, and "snow", "cloud", "melts", and "lakes and rivers" are each linked to three other concepts in this layer. "Evaporation" links to "water vapor" only which links to "cloud" and "rain". "Tiny droplets" link to "rain", but not to the condensation process that forms "clouds". "Run off" is missing, and "ground water" links to "lakes and rivers" and to "water", but not directly to "rain" or "land and soil". Although some elements of the hydrologic cycle appear, the development is not at the level of complexity found in cluster 6. See Figure 3.19.

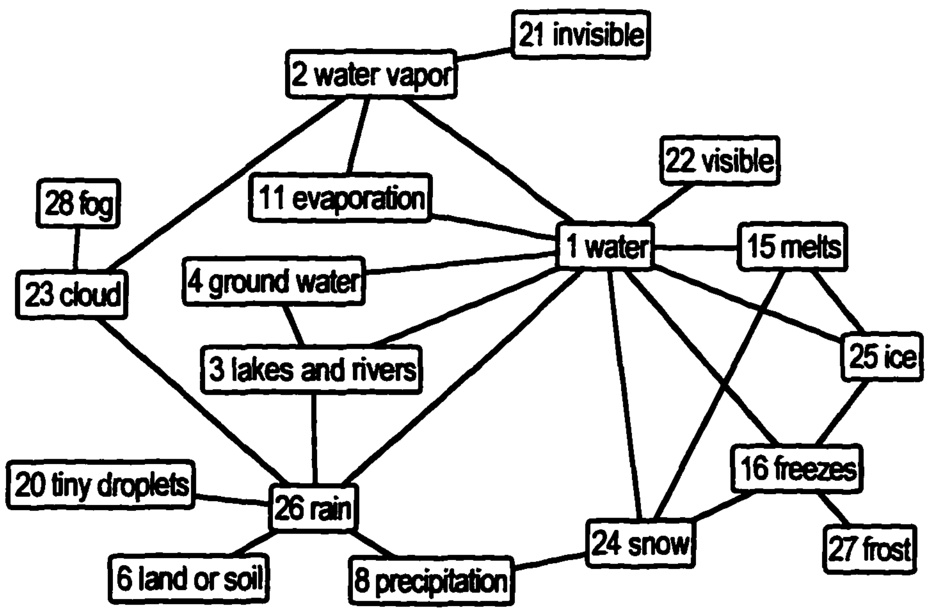

Figure 3.19. Composite concept map for Cluster 7 depicting relations constructed by at least twenty percent of the students. Numbers represent order in the concept set provided.

Differences in concepts used, concepts-connected, and structural characteristics of the composite maps provide further evidence that it is possible to discriminate clusters on the basis of similarities in concepts-connected, and the graphical differences predict a possible continuum in the development of understanding. The next section looks for objective criteria that may be used to order the composite maps in complexity or levels of understanding.

Several measures of comparison are selected to identify the levels of understanding represented in the composite maps. The number of concepts hints at scope of understanding, the ratio of concepts to relations is taken as a measure of complexity, and the number of concepts-connected to three or more other concepts is taken as a measure of concept development. The number of concepts in cyclic linkages, and the number of cycles consisting of three or more concepts may be evidence of integration of knowledge.

Strength is reported for each of the clusters. This measure is the average percent occurrence for the connections represented in the twenty percent composite. Cluster 3 and cluster 6 are the only clusters showing strong agreement for all represented connections. Clusters 1 and 4 have very weak agreement or low average percent occurrences for the connections shown. Table 3.20 summarizes some of the characteristics of the composite maps of these seven clusters.

Differences among the composites of the seven clusters appear to indicate levels of complexity and developing understanding. In the ordering shown in Table 3.20, the number of concepts used by at least twenty percent of the students increases while the ratio of concepts to relations decreases overall. Cluster 7 moved to a lower position in the sequence because the composite represented fewer concepts with at least three links to other concepts, had fewer concepts arranged in cycles and fewer cycles represented than cluster 6. Clusters 2 and 3 shared similar structural characteristics, however cluster 2 had more concepts involved in cyclic relations than cluster 3. Cluster 1 is composed of strands of concepts with no cyclic connections and shows the least complexity. Cluster six, with numerous cyclic connections, shows evidence of the most complexity on all criteria used.

Table 3.20

Characteristics of Composite Maps at the Twenty Percent Level of Occurrence for Concept Pairs Found in Maps of Clusters of Similar Concepts

	Clusters						
	1	3	2	4	5	7	6
Concepts	7	14	14	15	17	18	21
Concepts/Relations	1.333	0.875	0.875	0.833	0.739	0.692	0.750
Three+Connected	1	3	4	3	6	8	11
Cyclic Concepts	0	5	9	8	10	11	16
Three-Node Cycles	0	1	1	4	2	6	6
Four+ Node Cycles	0	1	2	0	1	6	6
Strength (%)	23	49	33	33	36	41	41
Level ofComplexity	1	2	3	4	5	6	7

Evidence of a continuum of learning.

Increasing complexity of the shared knowledge base represented by the composite map should indicate progressive levels of understanding. If these composite maps also represent a continuum of learning with incremental stages of learning, then each cluster in the order should become increasingly similar to the most complex cluster in this series. The next step in the analysis looks at the similarity measures for these composite maps.

A calculation of similarity ratios comparing concepts-connected in all composite clusters at the 20 % level reveals that clusters 5 and 7 are closest to cluster 6, but cluster 4 has less similarity to cluster 6 than cluster 3. The similarity ratios for concepts-connected in the seven clusters are shown in Table 3.21. Clusters are ordered by similarity to cluster 6 which is ranked highest in complexity.

Table 3.21

Clusters Compared with Cluster 6 and Ordered by Similarity Ratios for Concepts-connected

	Clusters						
	1	4	3	2	5	7	6
Concepts	7	15	14	14	17	18	19
Similarity to C6	0.100	0.189	0.194	0.303	0.389	0.472	1.000
Level ofComplexity	1	2	3	4	5	6	7

The previously established order is supported for all clusters with the sole exception of Cluster 4, which is rated a two on the basis of its dissimilarity to Cluster 6. Cluster 4, the exception in the series, deserves closer inspection.

If the relations of Cluster 4 are different, are they perhaps equally complex but based on a different framework than the other clusters? Although Cluster 4 includes fifteen concepts and appears to be a fairly complex structure, the relations are arranged in a star topology around the central concept water. “Precipitation” is linked to “water” and “rain”, but not to “cloud” or other forms of precipitation. “Ground water” links only to “water”, but not to “land or soil”. “Tiny droplets” are connected to “rain”, but not to “cloud” or the formation of “precipitation”. “Rain”, however, does link to “land or soil” and to “lakes and rivers”, and the water cycle is also shown in the connections between “water”, “evaporation”, and “water vapor”. Students also recognize that “water vapor” is “invisible” and that “fog” is related to “cloud”. “Snow”, “frost”, and “ice” link to "water" but not to "precipitation" or the processes "melts" or "freezes". Overall, the relations that are represented in Cluster 4 contribute little to the evolving structure of Cluster 6, and do appear to be organized around a slightly different framework that offers a crude outline of the movement of water in the water cycle.

Summary of Part I: Evidence for Developing Understanding Among Clusters of Maps

In summary, for this set of concept maps the percentage occurrence of specific concept pairs was seldom more than fifty percent, and for cluster 1 the highest percentage occurrence was under thirty percent. Therefore, the twenty percent solution was selected to represent an adequate sample of concept pairs for comparison. Composite maps showing concepts-connected in twenty percent of the maps of each cluster were converted to a graphical representation in KNOT-Mac, and some of the characteristics of these composite maps have been examined. Some objective criteria have found to be useful in ordering composite maps by complexity: the concepts/relations ratio, number of concepts in cyclic linkages, number and size of cyclic patterns in the map, number of fragments. At one end of the continuum, composite maps that show a low level of complexity consist of few concepts, have one or more fragmentary concept pairs, and have few relations overall. Structural patterns show simple strands of relations with little branching and no cyclic linkages. As the level of complexity increases, the number of concept pairs increases and the concepts per relations ratio decreases. Structural patterns increase in complexity with numerous branches and cyclic linkages between concepts.

Part 2—Evidence for Developing Understanding Across Grade Levels

An analysis of grade level distribution among clusters.

Further evidence for a continuum in understanding of the domain may be found in the relationship between grade level and the ordering of the clusters. Students in higher grades are expected to have more experience and better understanding of the domain, although overlap is expected among cross-age students. The next section looks for a pattern in the grade level distribution of maps in clusters ordered by complexity.

All clusters consist of maps from all grade levels, but what is the distribution of grade levels across clusters? Is there a relationship between the grade level of participants and the complexity or level of understanding represented in each of the clusters? In other words, are most sixth grade student maps found in the lowest clusters? and most twelfth grade maps found in the highest clusters? Table 3.22 shows the percentage distribution of students in the clusters.

Table 3.22

Percentage Distribution of Students by Grade Level in Clusters Ordered by Increasing Level of Complexity

Clusters	All	Grade 6	Grade 9	Grade 12
One	19.0	19.9	12.2	21.2
Three	7.1	6.9	8.8	6.8
Two	13.8	13.3	15.7	13.6
Four	20.4	22.7	24.6	14.4
Five	15.9	13.3	28	14.4
Seven	15.3	19.7	1.7	14.4
Six	8.5	4.4	8.8	15.2

Disregarding cluster 1 which consists of maps that are not very similar to maps of any cluster, the remaining clusters show some patterns of distribution. Twelfth grade students show a plateau of even distribution in clusters 4, 5 and 7 and show a slight increase in the highest level of complexity in cluster 6. The sixth and ninth grade students reach a peak in percentage distribution in clusters 4 and 5 respectively, then decrease membership in clusters of higher complexity. At the highest level of complexity, 4.4% of sixth grade students are represented, 8.8% of ninth grade students, and 15.2% of twelfth grade students. Figure 3.20 illustrates the normalcy of the distribution for clusters 2 through 7, ordered by complexity. The overall normal distribution pattern for these six clusters gives further credibility to the order of complexity assigned to the clusters.

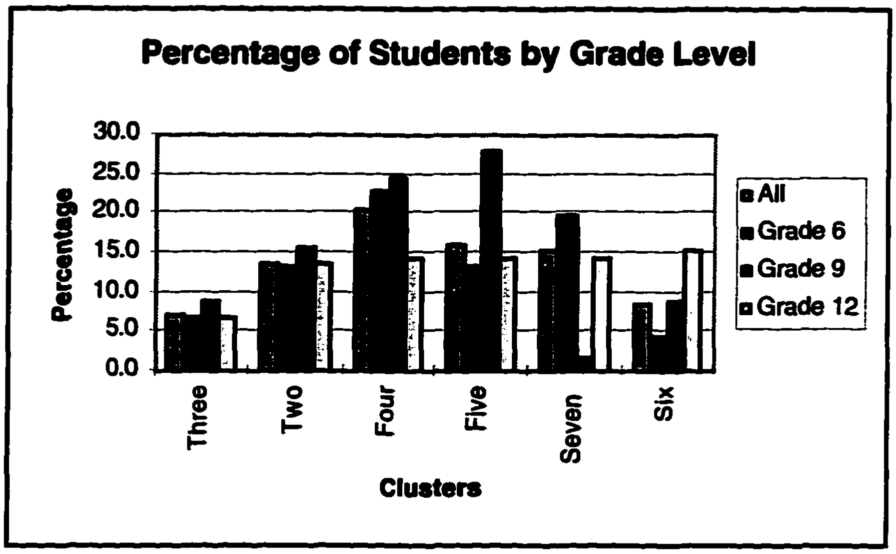

Figure 3.20. Distribution of all students and students by grade level for six clusters of maps having similar concepts-connected. Clusters are arranged in order of increasing complexity of the composites showing twenty percent agreement among the maps of the cluster.

Reasons for grade-level distribution across clusters.

The lowest bar for cluster 7 represents a single ninth grade concept map. Differences in perspective and depth of understanding may contribute to the finding that although more than twenty percent of several sixth grade classes constructed maps that are members of cluster 7, the ninth grade classes are minimally represented in cluster 7. Three characteristics of the cluster 7 composite support this finding. First, the concepts in the cluster 7 composite appear to be organized around two core concepts, "water" and "rain", which are directly linked. In the composites of clusters 5 and 6 these two concepts are linked indirectly through concepts such as cloud and precipitation, which infer richer understanding.

Second, the change of state is presented differently in clusters 7, 5, and 6. The one ninth grade student in cluster 7 included in his map the cycle "water—freezes—(ice):(frost)—melts—water" that is represented in the cluster 7 composite. The cluster 6 composite map also contains this cycle and minimally adds "freezes—snow". The cluster 5 composite map contains only the simple branches "freezes—ice—melts". The 28% of the ninth grade students in cluster 5 seem to include only a simple reference to change of state as they approach this mapping task from a different perspective.

A third difference between maps of cluster 5, 6, and 7 is found in the relations of the concept "groundwater". The cluster 5 composite map connects "land or soil—groundwater—water", but does not link "groundwater" to "lakes and rivers" as in clusters 6 and 7. Cluster 7 maps often connect "water—groundwater—lakes and rivers". The cluster 6 composite map shows more fully developed relationships with the connections "rain—land or soil—groundwater—runoff:lakes and rivers".

Differences in perspective are expected since the students were not given a framework for the connections. The perspective that each student adopts for the task may be rooted in classroom learning that immediately precedes the task, rooted in earlier formal or indirect learning, or founded in naive knowledge about the relatedness of the concepts.

To look for a possible link to classroom learning, Figure 3.21 shows a breakdown of cluster membership by class. Some patterns in distribution appear to correlate with class and teacher. No students in the sixth grade classes of teacher S, and few sixth grade students of teacher L placed in the highest rated cluster 6. Teacher S had not taught the unit on the water cycle prior to the mapping task. No ninth grade students of teacher D's second hour class placed in cluster 6 or 7; no student in his fourth hour class placed in cluster 7. The combined result is that the greatest percentage of ninth grade classes are in clusters 4 and 5. The greatest percentage of the sixth grade classes are found in clusters 1, 4, and 7. A low percentage of sixth grade classes are represented in the most complex cluster 6.

Grade twelve regular physics students are spread nearly evenly across all clusters, but a high percentage of four physics classes are found in cluster 1. Cluster 1 is characterized by unique relations and organization of concepts. Many maps of cluster 1 include non-viable relations and disorganized sequences that leave related concepts widely separated. "Water vapor", which is found to be a more interconnected core concept in maps of other clusters, is frequently isolated as a terminating concept or missing altogether from maps of cluster 1. The high percentage of twelfth grade students in cluster 1 is a concern since these maps are generally of lower quality than maps of other clusters. Lack of motivation may have contributed to the large population in cluster 1 since the mapping task was done at the close of the school year when there was little incentive for most twelfth grade students to perform well on an ungraded assignment.

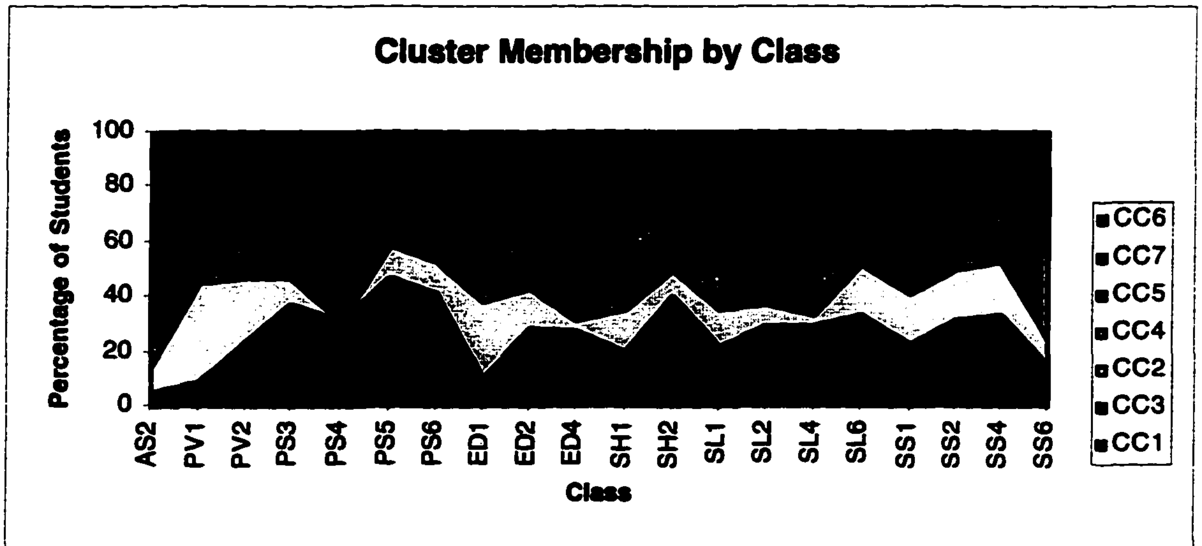

Figure 3.21. Classes sorted by grade level from advanced twelfth grade physics to sixth grade science show the percentage of each class in seven clusters of similar concepts connected ranked by complexity.

The Grade 12 Advanced Physics students are the exception. These students, their teacher observed, are typically highly motivated and have a strong science background. The pattern of cluster membership is more evident in Figure 3.22.

Figure 3.22 shows another comparison of the average percentages of each class in the seven clusters. The percentage distribution of each class across clusters is shown in Appendix G, Figures G1 through G3. Overall, the lowest ranked clusters tend to have higher percentages of classes of grade six and grade nine students; however, cluster 1 and cluster 2 each show an unexpectedly high percentage of students from some twelfth grade classes, followed closely by sixth and ninth grade classes. Cluster 3, the smallest group with only 27 members, is represented by similar percentages of students from all three grade levels. Cluster 4 is marked by higher percentages of sixth and ninth grade classes. Cluster 5 shows a high average percentage for ninth grade classes. Clusters 7 and 6 show high percentages of advanced physics students. The average percentage of regular grade 12 physics classes, although higher than the sixth and ninth grade classes, is lower than might be expected for clusters 7 and 6.

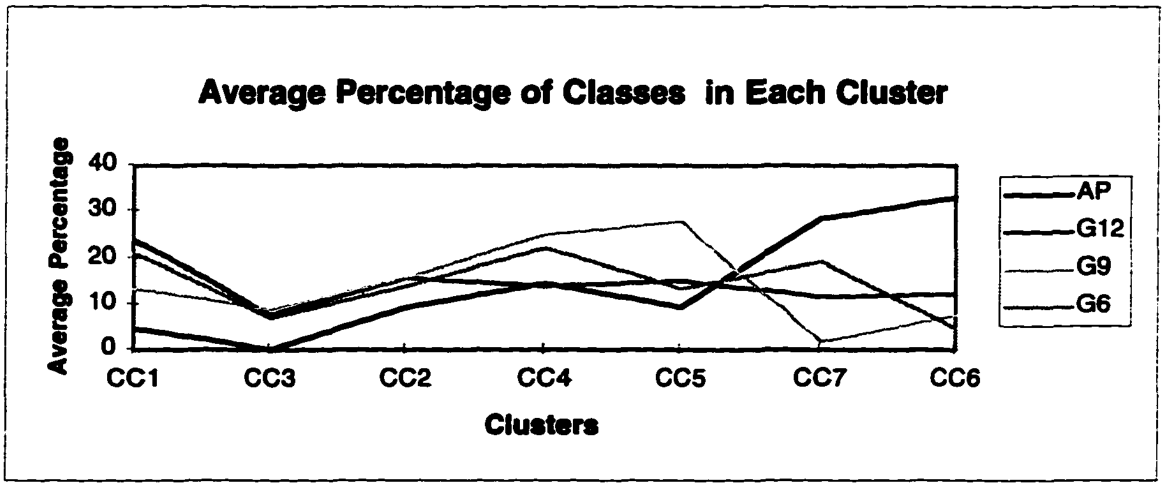

Figure 3.22. The average percentage of each class in each of the seven clusters of similar concepts-connected is shown. Clusters are ordered by complexity.

A pattern emerges for the advanced placement physics (AP) students: few of these students placed in the lowest ranked clusters; and overall, the percentage of advanced students in each cluster increases with the complexity of the clusters.

When clusters 5, 7, and 6 are considered together, about 70 percent of the advanced physics class is placed in this group. An average of 43.4 percent of each twelfth grade class placed in this group, while an average of 37.3 percent of each ninth grade class and an average of 36.5 percent of each sixth grade class placed in these clusters. Although the differences in distribution across clusters are not statistically significant, the patterns indicate a slight trend toward higher grade level membership in clusters representing concept maps of greater complexity. These findings support the expectation that there is considerable overlap in the knowledge of cross-age students; although generally more complex maps are produced by students at the higher grade levels, and simpler maps are constructed by students at the lower grade levels.

Considering the distribution across clusters, the study looks next at the concept maps of each grade level separately, although strong differences between them are not expected. The next section compares the composite maps of the three grade levels for discernible differences in their scope and complexity.

A comparison of composite maps for grades six, nine, and twelve.

For this analysis, the first composite map for each grade level is drawn to show the connections selected by at least 30% of all students at that grade level; a second composite map represents the connections selected by at least 15% of all students at that grade level. The thirty percent solution maps are first compared for evidence of increasing complexity.

The twelfth grade composite map shows concept pairs joined by at least 30% of the students. Eleven concepts are included, five of which are terminators on strands. Two concepts, "water" and "precipitation" have three or more links to other concepts. Each concept connected to "water" is further developed with the exception of "lakes and rivers". Weather processes are not evident in this map, but the movement of water in the water cycle is implied by the inclusion of "land or soil" and "lakes and rivers". Changes of state are also represented. See Figure 3.23.

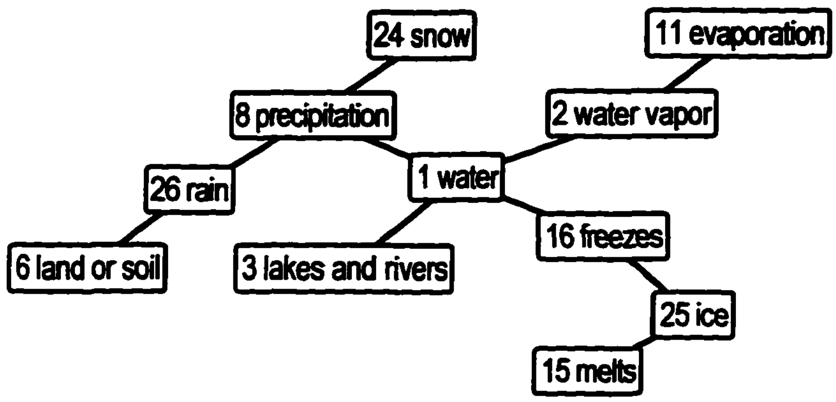

Figure 3.23. Composite concept map for Grade 12 depicting relations constructed by at least thirty percent of the students.

The ninth grade composite map in Figure 3.24 depicts concepts connected by at least 30% of the students. An isolated subgroup of "ice—freezes" is evident. The concepts appear to relate to the geologic study of erosion recently completed in the course. "Runoff" connects to "lakes and rivers" but not to "rain" or "groundwater". "Water vapor" connects only to "water", not to "precipitation" or "evaporation". The link between "rain" and "water" may be considered redundant, and seems to contribute no added meaning. The same can be said for the connection between "groundwater" and "water". An analysis of the linking phrase selected by these students may clarify the connection. Altogether, strands are less developed than in the twelfth grade concept map, and a higher proportion of the concepts are terminators.

Eleven concepts, including the concept "cloud" which does not appear in the other composite maps at the thirty percent level are used in the sixth grade maps. At this level at least, "cloud" does not link to "precipitation", but a framework is developing that includes weather and the movement of water in the water cycle. The link from "lakes and rivers" to "water" adds no apparent meaning. "Evaporation" links the transition from "water" to "water vapor". An isolated subgroup linking "freezes—ice—melts" is included in Figure 3.25.

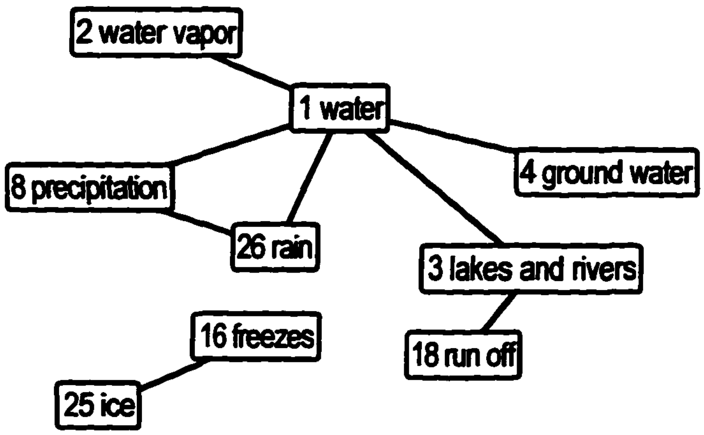

Figure 3.24. Composite concept map for Grade 9 depicting relations constructed by at least thirty percent of the students. Numbers represent order in the concept set provided.

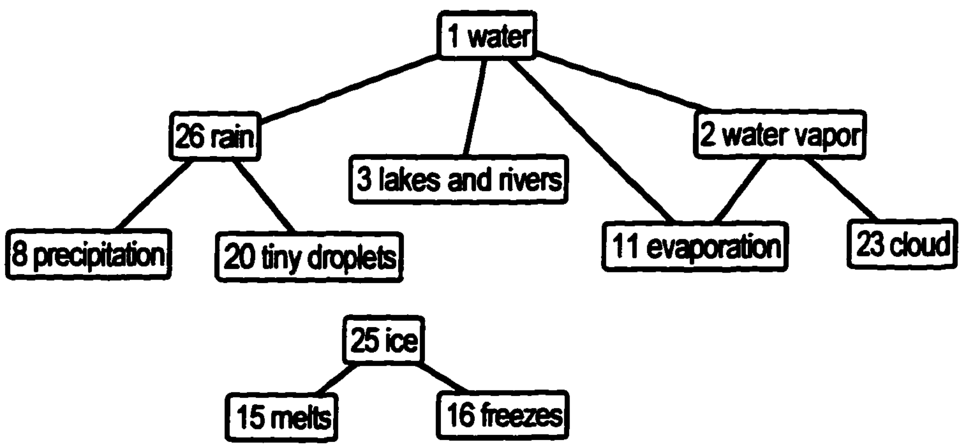

Figure 3.25. Composite concept map for Grade 6 depicting relations constructed by at least thirty percent of the students. Numbers represent order in the concept set provided.

An objective comparison of the three composite maps examines some of the structural characteristics of the maps as a basis for ordering by complexity as shown in Table 3.23.

Table 3.23.

Characteristics of Composite Maps at the Thirty Percent Level of Occurrence for Concept Pairs in Maps of Each Grade Level

	Grade		
	6	9	12
Concepts	11	9	11
Concepts/Relations	1.10	1.125	1.10
% Terminators	54.5	44.4	45.4
Three+Connected	3	1	2
Cyclic Concepts	3	3	0
Average Strength	38	40	40
Level of Complexity	3	2	1

Considering the structural characteristics of the three maps, the twelfth grade composite may be ranked most complex, and the sixth grade map, least complex. The sixth grade shows slightly less strength for the composite, meaning that the average percentage of students selecting each link is slightly less than for the ninth and twelfth grade composites. The higher percentage of terminators indicates that the composite structure is not as well integrated as the twelfth grade map which uses the same number of concepts.

Similarities ratios for the composite maps may also be compared. Between the sixth and twelfth grade composites at the thirty percent level there is a 69.2% agreement in the concepts used; the ninth grade composite uses 53.8% of the same concepts as either the twelfth or sixth grade students. When connections between concepts are compared, there is closer agreement between the twelfth and sixth grade students with 42.9% similarity in concept pairs; the ninth grade composite has an agreement of 38.5% with both twelfth and sixth grade. The closer agreement between twelfth and sixth grade maps at the thirty percent level indicates that both groups are operating on the same framework; the ninth grade map includes concepts and connections that directly relate to earth science.

There are no dramatic differences between the three grade levels when all connections selected by at least thirty percent of the students are considered. A second set of maps at the fifteen percent level, shown in Figures 3.26, 3.27, and 3.28, draw similar comparisons although the number of concepts used and connections formed increases.

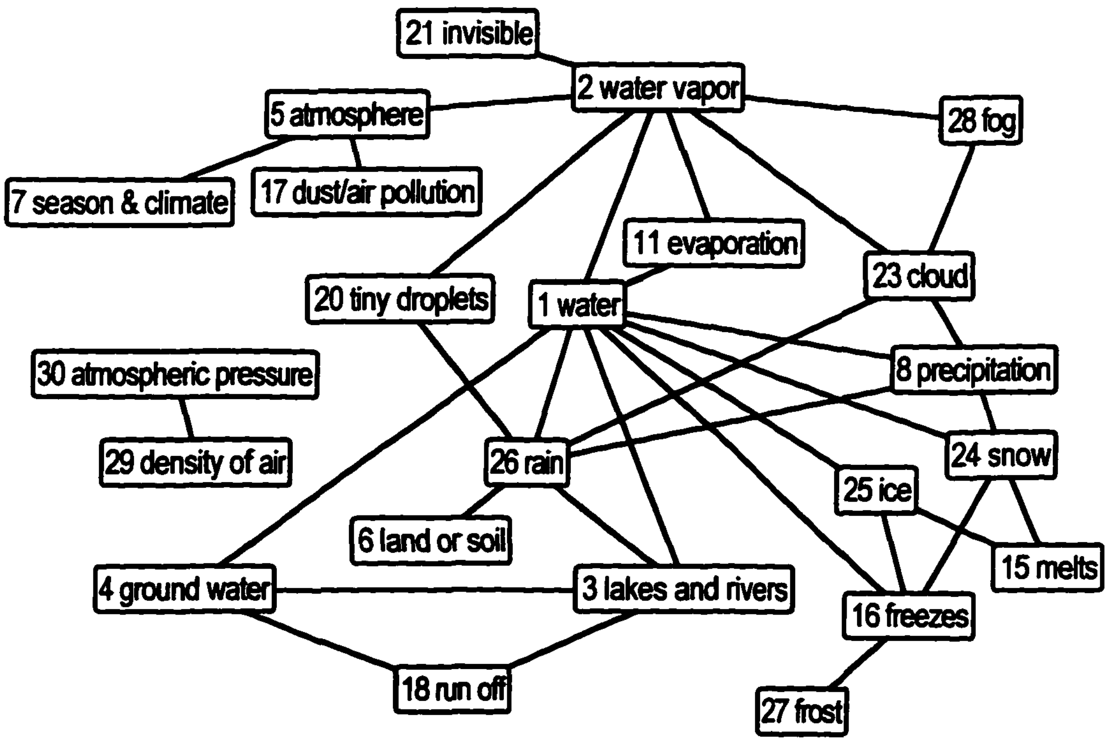

Figure 3.26. Composite concept map for Grade 12 depicting relations constructed by at least fifteen percent of the students. Numbers represent order in the concept set provided.

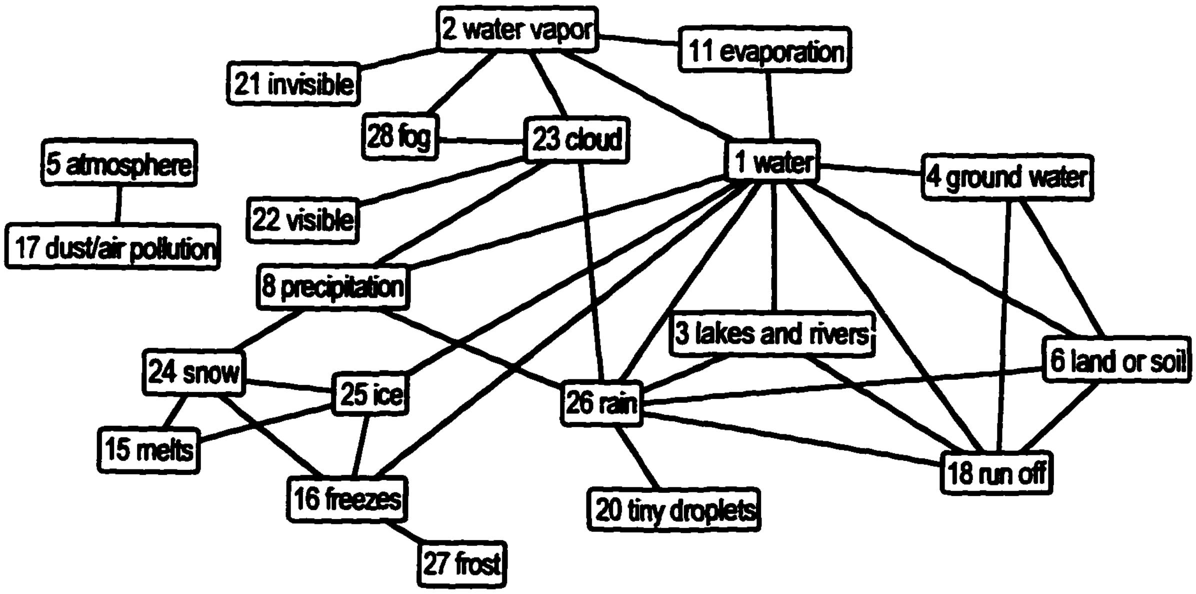

Figure 3.27. Composite concept map for Grade 9 depicting relations constructed by at least fifteen percent of the students. Numbers represent order in the concept set provided.

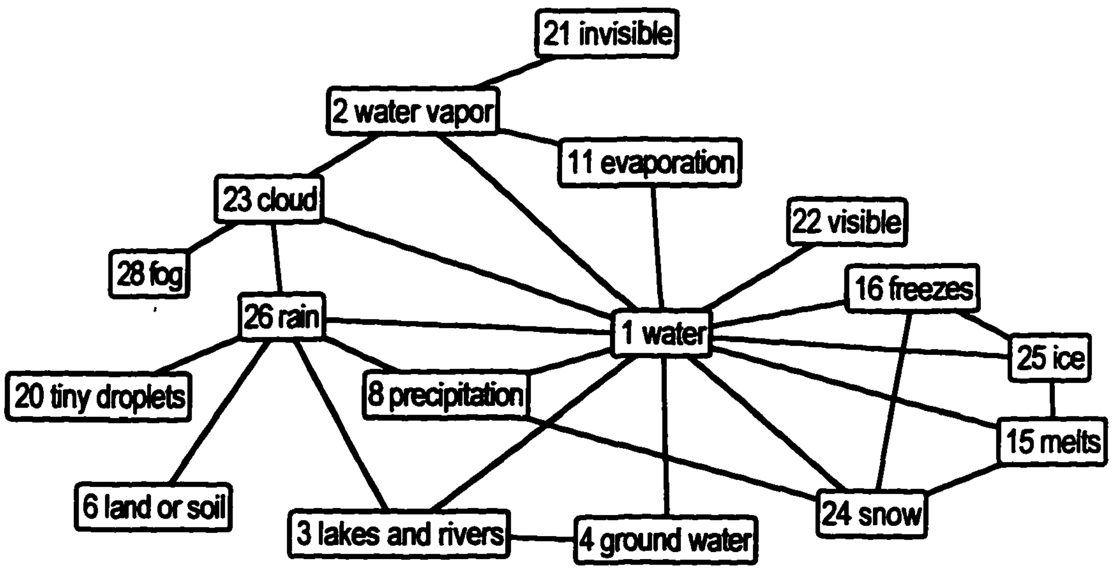

Figure 3.28. Composite concept map for Grade 6 depicting relations constructed by at least fifteen percent of the students. Numbers represent order in the concept set provided.

Table 3.24.

Characteristics of Composite Maps at the Fifteen Percent Level of Occurrence for Concept Pairs in Maps of Each Grade Level

	Grade		
	6	9	12
Concepts	17	21	23
Concepts/Relations	0.630	0.600	0.697
% Terminators	29.4	14.3	18.2
Three+Connected	10	12	11
Cyclic Concepts	12	15	15
Average Strength	26	27	26
Level of Complexity	3	1	2

Even at the minimum of fifteen percent level of agreement for connections represented the differences between the grade level composite maps are disappointingly subtle. When similarity ratios are calculated for the 15% solution, grade six and grade nine are most similar with 85.7% of the same concepts, however the similarity for concepts connected is only 59.0%. The similarity ratio for grade nine to grade twelve is 83.3% for concepts used, and 65.9% for concepts connected. Between grade twelve and grade six, the ratio is 70.8% of the same concepts used, and 62.2% for concepts connected. This finding supports the ranking by complexity for the fifteen percent solution that places the grade twelve composite between the grade six and the grade nine maps. This finding indicates that less than fifteen percent (if any) twelfth grade students formed the complex interconnections that were predicted for students who had experienced the full range of the science curriculum. Grade six maps were less developed than the grade nine maps; some of the concepts learned in the earth science curriculum are evident in the ninth grade maps.

Summary of Part II: Evidence for Developing Understanding Across Grade Levels

In summary, there are some discernible differences between the composite concept maps of the three grade levels, and they can be weakly ranked on the basis of increasing complexity that corresponds to increasing grade level for the thirty percent solution maps. Evidence for continuity is shown in the similarities in concepts-connected: four concept pairs are found across all three composites, and two additional concept pairs matched between the sixth and twelfth grade composites. At the thirty percent level, the framework of the ninth grade composite differs from the others and appears to be organized around concepts that the students might have considered in the context of their geologic study of erosion.

The fifteen percent solution includes a broader range of concepts and connections across maps of all three grade levels. The ninth grade composite map is slightly more complex than the twelfth grade composite, and when similarity ratios are calculated for concepts-connected, the twelfth grade composite at the fifteen percent level falls between the sixth and ninth grade composites. The expected higher level processes and concepts, richness, and complexity are not evident in the twelfth grade composite map.

Summary

This study concludes that it is possible to identify a progression of learning by analysis of language-constrained computer-assisted concept maps that includes clustering by construct similarities such as concepts-connected, and the generation of a composite map for the cluster that represents connections having at least the specified percentage occurrence. This study shows that slicing through the composite concept map at different percent occurrences for concept pairs can graphically represent the strongest connections.

This technique provides an holistic view of what ideas are most commonly held by students and how they connect these ideas together.

In Part I of this study, composite concept maps representing the clusters of maps having similar concepts-connected depicts connections of at least twenty percent occurrence so that an adequate sample of concept pairs would be shown for all clusters. This method provides evidence for a progression in levels of complexity of the composites, based on structural characteristics such as the number of concepts, number of concepts with three or more connections to other concepts, the ratio of concepts to relations, the number of cyclic structures in the composite, and the number of concepts in cyclic structures. Analysis of structural characteristics provides evidence that the maps of Cluster 1 represented the lowest level of understanding of the domain. Cluster 1 consisted of maps that do not find corresponding matches to maps of other clusters and little similarity to maps within the cluster. Cluster 1 maps are characterized by alternative conceptions and differences in organization of core concepts. When clusters two through seven are ordered by level of complexity and compared for overall distribution of students, a relatively normal distribution is found which provides supporting evidence that the selected criteria order the clusters appropriately.

Further evidence supporting the order of progressive complexity and developing understanding is shown when composite maps, ordered on the basis of their similarity ratio to the most complex cluster, maintain the order derived by the comparison of other structural characteristics. One cluster, cluster 4, deviates from the original order of complexity. The increasing similarity to cluster 6 indicates a continuum of the represented learning as the learning develops. In other words, as the complexity of the maps increase, students are shown to build on the same framework.

Part Two of this analysis has shown a large overlap in the understanding of students in grades six, nine, and twelve when all concept maps are compared for similarities. Students of all three grade levels were represented in every cluster. Students in grade six are generally expected to have a less understanding of the domain than ninth and twelfth grade students. Generally high percentages of sixth and ninth grade classes are represented in the clusters of lower complexity. The three clusters rated most complex show a higher percentages of classes of twelfth grade students, followed by ninth and sixth grade students. This finding supports a continuum of developing understanding evidenced in the clusters where, overall, more students in lower grade levels depict less complex maps and more students in upper grades depict more complex maps.

An unexpectedly high percentage of twelfth grade students in four classes are found in cluster 1. It is possible that motivational factors played a role in the task performance. The alternative conceptions and apparent disorganization of maps in cluster 1 may not reflect accurately the students' level of understanding.

When Cluster 1 is disregarded and clusters two through seven are ordered by level of complexity (but not by similarity to cluster 6) and compared for the number of students at each grade level, a pattern of normal distribution is found for the sixth and ninth grade students. Twelfth grade students' distribution plateaus across clusters 4, 5, and 7, and rises slightly for cluster 6 which as a group represents the highest level of complexity among the concept maps.

This study asked whether for sixth, ninth, and twelfth grade students, a comparison of their composite maps of a domain would indicate an increase in the extent of the contiguous core framework. This study does not find a notable difference at the 30% level of occurrences of concepts-connected in the extent of the contiguous core framework of sixth, ninth, and twelfth grade composite maps. Considerable diversity in concept pairs is found among the three composite maps with a total of seventeen concept pairs identified at the 30% minimum level. Evidence is found for continuity of learning in that some similar concept pairs are identified in all three composite maps.

The number of concepts and relations for sixth and twelfth grade students are similar in the composites compared. Five concept pairs are matched between the sixth and twelfth grade composite; however, the composite thirty percent map for grade twelve shows slightly more complex structural characteristics. The evidence of dissimilarity in the ninth grade composite may be attributed to the contextual framework used by some ninth grade students to relate the concepts to geologic studies.

No major difference in the extent of fragmentation is found among the composites. Both grade six and grade nine composites for the thirty percent solution shows one fragment consisting of one or two concept pairs separated from the main group. All three grade levels show a similar shared understanding of the domain. Therefore, a comparison of the composites for the grade levels shows only subtle differences between them.

The comparison of the fifteen percent solution for the three grade levels shows that few students at each of the grade levels selected the more complex relations. Higher level concepts are still missing from all three composites. Subtle variations in complexity are seen; however, the ninth grade composite is judged to be slightly more complex than the twelfth and sixth grade composites.

In conclusion, Study 4 shows that a comparison of language-constrained computer-assisted concept maps does reveal patterns of increasing complexity of maps as competency increases. Similarity measures comparing the composite concept maps or ordered clusters reveal a progression in similarity to the most complex composite map. This finding affirms that many students who experience a similar curriculum build on the same framework for the domain as they progress through grade levels. These findings seem to indicate that the biology, chemistry, and physics curriculum in grades ten, eleven, and twelve have had little influence on how students see this set of concepts to be connected. Furthermore, some learning from ninth grade experiences may have been lost or not immediately available to the twelfth grade students as they performed this task.

CHAPTER IV

DISCUSSION

Overview

Scientific literacy implies that students understand the complex interconnections of science concepts. The connections that students make between concepts in a domain can indicate whether students have the fundamental framework of connections in place and readiness for new learning, or whether students understand the interrelationships in a domain. Concept mapping has long been recognized as an effective means of representing connected knowledge. Concept mapping has had broad application as a tool for curriculum planning, for instruction, for learning, and for the assessment of student understanding of a complex web of knowledge; however, the challenges associated with traditional methods of constructing concept maps and then evaluating them have limited the application of concept mapping in classroom practice. A technological approach to concept mapping is used in this dissertation to probe the understanding of a science domain for students in a school learning environment.

Summary of the Purpose of the Dissertation

One purpose of this dissertation is to identify patterns in the understanding of a science domain for a large number of cross-age students using a technological approach to the construction and evaluation of concept maps. Another purpose is to learn whether there are commonalities in the way students represent ideas in a domain, and whether a progression in learning is evident in cross-age concept maps of students who have experienced a similar curriculum.

Contributions to the Methodology of Concept Map Construction and Analysis

This dissertation develops and implements a methodology for the comparison of concept maps that looks for similarities in the way students see connections between ideas. From clusters of similar maps emerge patterns of connections that indicate differences in understanding among groups of students. The focus of this analysis of concept maps is not on rating the individual map, but rather on determining the interconnections between core concepts for each group of students who have represented the domain in a similar way. This holistic approach to the evaluation of configural properties of concept maps has implications for instructional planning and curriculum evaluation.

In order to accomplish the purposes of this dissertation, the methodology builds on prior research and addresses five needs: 1) an efficient method of constructing and analyzing large numbers of concept maps; 2) a common construction set to facilitate comparison of maps; 3) a method of encoding concept maps for comparison; 4) an algorithm to calculate the similarities between two maps; and 5) a method of identifying clusters of similar maps. The methodology of studies included in this dissertation depends on several software tools for the construction, comparison, analysis of concept maps.

The first three needs are addressed by the development of a new software program for the construction of concept maps. Existing software programs such as SemNet (Fisher, 1994, 1990) have responded to the need for an efficient tool to produce concept maps using freely-selected terms. Existing programs are designed on the premise that each learner creates a unique representation of a domain using unique language components. Novak and Gowin (1984) and Champagne, Kloppfer, Desena and Squires (1981) have reported some consistencies in students' selection of terms to describe relationships in a domain, and prior research has validated the use of language-constraints for mapping tasks. This dissertation contributes The Computer-assisted Concept Mapper (CCM) as a new tool designed for language-constrained concept mapping that provides a basis for the analysis of concept maps that would not be practical without technology. CCM allows the teacher to provide for students a set of concepts and linking phrases appropriate to the domain. Students use CCM in a manner analogous to drawing a concept map, moving and connecting concepts to show how the ideas are related.

If a common construction set of concepts and linking words is provided, then direct comparison of concept maps is possible when the topology of the concept map is reduced to coded concept-link-concept segments for comparison. This methodology assigns a number to each concept and a letter to each linking phrase. When the student saves the concept map, CCM converts the map to a list of triads such as 2b5, 1a3 that are similar to the representation of labeled graph elements. Triads allow structural elements of the concept map to be manipulated and compared. Meanwhile, the context of relations is preserved, composites can be formed, and the original concept map can be reconstructed in an equivalent topology.

The fourth need is for an algorithm for the comparison of two maps. Pathfinder networks are compared using the C-measure algorithm developed by Goldsmith and Acton (1991) that considers the neighborhood of each node or concept in two maps and determines a ratio of similarity for each node, then sums node ratios to obtain a map ratio. The C-measure assigns all nodes equal value, regardless of the number of links to the node. One difference between Pathfinder and the concept mapping in this dissertation is that Pathfinder demands that students rate all pairs of concepts and therefore always includes all concepts. Concept maps may consist of a subset of the concepts provided. The methodology in this dissertation adapts the C-measure algorithm for the comparison of two concept maps. The modification for this dissertation assigns all relations equal value by comparing similarities over the entire map in a single calculation.

Another difference between Pathfinder and concept mapping is that Pathfinder connects concepts based on a closeness rating. Relations between concepts are not defined and have no intended directionality. The more complex structural features of concept maps allow comparisons on several levels. The methodology in this dissertation extrapolates the evaluation of Pathfinder networks to the evaluation of concept maps in which structural components of concept maps become the basis for the comparison. Pairs of maps are compared for concepts used, concepts-connected, linking phrases used for relations, and directionality of the relations, with each level of comparison adding another requirement for the congruency between the maps. The comparison of concept maps is achieved with The Concept Map Analyzer, a new Hypercard stack developed for this dissertation. The calculation of the similarity ratio or percentage of similarity between every pair of concept maps is the first step toward further and more meaningful analysis. The similarity ratio is the first step taken to discriminate concept maps and identify groups of maps that show ideas connected in the same way.

The fifth need is a method of identifying clusters of similar maps without pre-assigning the number of groups or group membership. The methodology developed and used in this dissertation utilizes cluster analysis to sort concept maps into clusters of similar maps based on the similarity ratios for all pairs of concept maps. Maps in each cluster have similar ratios and exhibit some patterns in connections and shared understandings of the domain.

This dissertation applies a methodology that addresses the five needs related to the construction and analysis of concept maps. The dissertation is organized around two questions that spawn four studies which are discussed in the next sections. Two concept domains are utilized. The first two studies use concepts from an instruction-free food domain. Studies 3 and 4 utilize a domain of concepts related to the water cycle. The water cycle domain was selected because depth of learning about the complex relationships among these concepts is expected to develop as students progress through the prescribed K—12 science curriculum.

Summary of the Findings of the Dissertation

Summary of Question 1

The first question of this dissertation asks whether constrained concepts and linking words can be used to produce valid computer-assisted concept maps that can discriminate students on their knowledge of the domain. This question is answered in two parts, first, by validity and reliability tests, and second, a discrimination study.

Study 1: The Validity of Language-constrained Computer-assisted Concept Mapping

Study 1 affirms that The Computer-assisted Concept Mapper as a tool has construct validity in that students generate concept maps similar to those produced by pencil and paper techniques. Study 1 demonstrates consistency between two techniques of producing language-constrained concept maps. The concept maps produced with CCM are similar to those produced with pencil and paper in concepts-connected and in the way students selected linking phrases to describe relationships. The number of concepts, concept pairs, and number of relations (concept-link-concept units) in the two sets of language constrained maps are very similar, and the average similarity measure between the two types of maps is 0.535 indicating an average agreement of 53.5% of the connections between concepts when pairs of maps of both types are compared. These results are in accordance with the expectation that the task may be done differently in repeated tests while maintaining a basis of similarity. Considering the number of possible pairs among the thirty concepts provided, a 50% and more agreement for concepts-connected in maps produced with the two mapping techniques may be considered substantial similarity.

When the two types of language-constrained maps are compared across maps for each grade level, namely, a comparison of all sixth grade paper and pencil maps compared with sixth grade computer-assisted concept maps, no significant difference is found in the number of concept pairs, common concept pairs, number of relations, and common relations for each set of maps. Further, a comparison of the connections to each concept across maps of each type shows that the same concepts in both types of maps had the most links to other concepts; both types of maps have the same rank order and similar numbers of links to other concepts, evidence that the concepts were used in the same way in both types of maps.

When the pencil and paper maps of all students are compared to the students' CCM concept maps using similarity calculations, similarity ratios confirm that each student's own two maps are more similar to each other than to maps of other students. This finding shows that the student produces similar maps whether using pencil and paper or the CCM tool.

Concept maps constructed with the CCM tool show that students working with the same construction set produce different concept maps. Variation in concepts-connected and selection of linking words is characteristic of the idiosyncrasy of freely-drawn concept maps. Therefore, the ability to produce unique concept maps is further evidence for validity of the computer-assisted mapping tool.

This collective evidence shows that CCM can be accepted as a valid technique and an analog to traditional concept mapping since it operates similarly enough to concept mapping in general and shows similarity between language-constrained concept maps produced with pencil and paper and with the computer-based tool.

Study 2: The Reliability of Language-constrained Computer-assisted Concept Mapping

Study 2 demonstrates the reliability and consistency over time of the concept maps produced by the student using CCM. Study 2 confirms that students using CCM generate similar concept maps in two sessions one week apart. When the language-constrained computer-assisted concept maps produced in the two sessions are compared, evidence shows that, overall, 46% of the relations found in the first set of maps are found identically represented in the second set of maps. In addition, 23% of the connections included in each student's first map are found in the second map, but with a change in the linking phrase or direction of the link between the two concepts. Overall, a comparison of the first and second sets of maps shows that the ratio of identically represented relations to modified relations is about 2:1. In other words, on the average, about two-thirds of the relations that are found in both of the student's maps are represented in exactly the same way as they were originally. Some changes are expected when students re-draw traditional pencil and paper concept maps. Therefore, this finding affirms the ability of the tool to represent ideas consistently.

At least sixty-nine percent of the concept pairs represented in the first map reappeared in the second map, evidence that less than 31% of the connections included in the first set of maps are missing in the second set of maps. Students either did not connect the two concepts, or related the two concepts indirectly by a connection to one or more other concepts. Overall, the ratio of recurring concept pairs to missing concept pairs is about 2:1, a finding which further supports the reliability of the tool.

Collectively the evidence shows that the relations represented in each student's first map indicate reasonable stability in the second effort, a finding that supports the reliability of language-constrained concept mapping.

Together, Study 1 and Study 2 demonstrate the validity and reliability of The Computer-assisted Concept Mapper as an alternative method of producing language-constrained concept maps. Other mapping software such as Sem-Net focuses on free-mapping strategies, and between map comparisons are difficult or impossible. Evaluation focuses on characteristics of individual maps and individual map scores. Groups based on these scores do not necessarily represent ideas the same way. Word association studies including Pathfinder do not include the depth of defined relationships and directionality that are shown in concept mapping, but they do permit comparisons between students. The primary benefit of CCM's use of a language construction set is the ability to directly compare student concept maps even to the level of defined relationships. The next section summarizes the findings of Study 3 which shows the effectiveness of the tool in discriminating concept maps.

Study 3: The Discrimination Ability of Language-constrained Computer-assisted Concept Mapping

Study 3 affirms that a language-constrained computer-assisted concept mapping task can discriminate students on their understanding of the knowledge domain. The support for this statement is found in the following evidence.

Discrimination ability of the analysis tool.

This dissertation concurs with prior findings of Regis and Albertazzi (1996) that concept maps created with the language "building blocks" are unique structures, not in their elements, but in the way these elements are assembled. Despite the uniqueness of individual perceptions, this dissertation shows that some commonalities emerge in the way students see interconnections between ideas. The findings of this dissertation demonstrate that concept maps can be compared and grouped on the basis of similarities in the structural units by a method analogous to graph analysis.

Analysis of structural components of concept maps can discriminate concept maps. When concept maps are compared for similarities based on concepts used and concepts-connected, a range of similarity ratios is evidence that some maps are alike in the characteristic and that maps differ from others. When the similarity data is subjected to cluster analysis, groups of similar maps are identified. The identification of clusters of similar maps confirms the ability of the analysis tool to differentiate students on the basis of their expressed knowledge of the domain.

In Study 3, students were not required to use all concepts. Evidence shows that when students can choose not to use all concepts, clusters of concept maps consisting of similar concept sets can be identified. These clusters of concept maps consist of similar concept sets that differ both in numbers of concepts and in specific concepts used. Clusters of concept maps consisting of similar concept sets may differ in whether all concepts are used, some concepts are used in all maps of the cluster, or some concepts are not used by any member of the cluster. Certain concepts are more discriminating than others as evidenced by their wide range of occurrence across the clusters.

Characteristics of similar concepts-connected clusters are evident in Study 3. Evidence shows that clusters of concept maps consisting of similar concepts-connected differed in the average number of concept pairs per map, the number of unique concept pairs identified in the cluster, specific concept pairs, and the number of connections to core concepts. Some concept pairs are discriminating, having a wide range of percent occurrence across clusters. The most discriminating concept pairs in Study 3 have a greater than 30% occurrence in only one to three clusters, or they exhibit a wide range of percent occurrence across clusters.

Although clustering on the basis of similarities in linking phrases and directionality would be possible, this dissertation does not pursue that level of comparison. For this data set, the low similarity measures for choice of linking phrases and directionality of the links indicates that, even when students connect the same concepts, a different linking phrase may be attached. Similarity ratios for directionality are correspondingly low since the layers of similarity are compounded in the comparison.

Evidence in Study 3 has shown, however, that concepts selected and concepts-connected do discriminate language-constrained concept maps. Comparison of linking phrases and directionality adds a depth of information about relevant links. This dissertation uses linking phrases with a range of complexity. The expectation in the research design of this dissertation is that students at a lower level of competency will choose the simpler linking phrase for a given relation. Observation shows that the complex linking phrases such as "absorbs heat energy" or "releases heat energy" were rarely applied by students, although they were intended for use in describing processes of melting and freezing, for example. The observation in this dissertation seems to concur with the findings of Groulx and Danssereau (in Jonassen, Beissner, & Yacci, 1993) that the use of fewer phrases and categorical phrases that have very clearly defined application are expected to show more agreement in usage. Even ten linking phrases are more difficult for students to apply. The complete analysis of linking phrases and directionality are not essential to show the viability of the analysis tool and are not pursued here.

The identification of clusters of similar maps confirms the ability of the tool to discriminate maps, but this is only part of the answer. Do the maps of different clusters reflect different levels of competency? The next section summarizes the findings related to competency levels.

Map clusters and competency level of students.

Study 3 affirms that students of the same level of competency or grade level show a similarity between their concept map and that of other students of the same competency level. Evidence showed that students of the same competency or grade level construct concept maps that are similar in concepts selected and concepts-connected. For example, in Study 3, the average number of concepts used by sixth grade students is significantly lower that the average number of concepts used by twelfth grade students; no significant difference is found for ninth grade students when compared to the sixth and twelfth grade students. The same pattern is evident in a comparison of concepts-connected. The average number of concept pairs connected by sixth grade students is significantly lower than the average number of concept pairs connected by twelfth grade students; no significant difference is found for ninth grade students.

As in the research of Novak and Mussonda (1991), some knowledgeable students at lower grade levels are found to have the same level of understanding as some students at higher grade levels, and some less knowledgeable students at higher grade levels were found to have the same level of understanding as some students at lower grade levels. Study 3 indicates considerable overlap in levels of understanding across grade levels for this domain and for this population. All clusters, whether based on concepts selected or concepts-connected, were comprised of students from all three grade levels in varying percentages. When clusters grouped by similarity in concepts-selected are arranged by increasing average numbers of concepts per map, the distribution of sixth, ninth, and twelfth grade students decreases by increasing grade level for the lowest four clusters, and increases by increasing grade level for the highest four clusters. For example, the lowest clusters in the order have the lowest average number of concepts per map and a large distribution of sixth grade students, but fewer ninth and twelfth grade students. The number of concepts used in the map appears to be related to the competency level of the student. The specific concepts selected differ somewhat across competency levels. Process concepts are used less often in sixth and ninth grade maps. When compared to twelfth and ninth grade maps, fewer sixth grade maps include the concepts "precipitation", "groundwater". "runoff", "atmosphere", "density of air", and "season and climate". Study 3 shows that students' maps are similar to those of other students of the same competency level when maps were clustered by concepts selected.

As with concepts used, similar patterns are observed for clusters of maps grouped by concepts-connected. Although all three grade levels are represented in each cluster, the overall pattern of distribution indicates that students' maps are similar to those of other students of the same competency level when maps are clustered by concepts connected.

One explanation may be that students of lower competency may be unfamiliar with some of the concepts and simply choose to use fewer concepts. These students may also take more time to think about the connections between the ideas with the result that they produce more limited concept maps in the time provided. Overall, the identification of clusters that exhibit distinguishing characteristics of numbers of concepts and specific concepts-selected affirm the ability of the analysis tool to discriminate students on their understanding of the domain. The distribution of students of different grade levels across clusters ranked by number of concepts and pairs of concepts is evidence that students of the same competency level construct similar maps. This statement recognizes the overlapping competency of students in different grade levels while making the assumption that in a normal distribution of a population, more sixth grade students would have a lower competency within the domain than ninth or twelfth grade students.

Study 3 demonstrates that Pathfinder analysis can be extrapolated to the analysis of structural elements of concept maps to identify maps that show similar connections. Goldsmith and Johnson (Schvanevelt, 1990, chap. 17) indicate that student (Pathfinder) maps may be compared to one another to identify configural similarities that indicate levels of understanding. This dissertation shows that clusters of similar concept maps can be identified, and that these clusters have distinguishing characteristics that indicate differences in understanding of the domain.

The increase in the number of concepts or concepts-connected across clusters does not indicate nor preclude a progression of learning across the clusters of similar maps. Is there a pattern that suggests an expanding core framework across clusters? The clusters identified in Study 3 are used again in the next part of the dissertation to answer that question.

Summary of Question 2

The second question asks whether the comparison of clusters of similar language-constrained computer-assisted concept maps reveals patterns in the continuum in understanding of the domain. This question is answered by Study 4; the findings are summarized in the next section.

Study 4: Evidence for Levels of Understanding of the Domain

Study 4 demonstrates a methodology that identifies among clusters of concept maps a progression of student learning. Maps can be ranked based on features such as number of concepts used, concepts/relations ratio, evidence of cyclic patterns of relations and multiple connections to core concepts which indicate a richness and complexity of representation. The Concept Map Analyzer compares slices of composite maps to calculate similarity ratings between them for evidence of a progression of similarity.

This analysis affirms that a continuum in understanding of the domain is shown in the patterns of knowledge represented in clusters of concept maps. The evidence is shown in a two-part study. Part One of Study 4 affirms that clusters of similar maps, grouped by concepts-connected, show a continuum of developing understanding in patterns of knowledge structures representing of the domain. To summarize the structure for each cluster, the maps are aggregated into a composite map. Slices of composite maps are generated for the seven concepts-connected clusters in Study 3 to show only those concept pairs that appear in at least 20% of the maps in the cluster.

The composite maps are rank ordered on the basis of increasing numbers of concepts used, increasing number of interconnections between concepts, and an increase in cyclic relations. Evidence shows that, for Study 4, a more complex framework evolves over the ordered composite maps. Cluster 1, which is ranked least complex, shows no particular framework and engages few concepts. At the other end of the spectrum, Cluster 6 has the most comprehensive framework and incorporates phase changes, as well as atmospheric and land aspects of the water cycle. Cluster 6 is the first cluster to include "atmospheric pressure" and "density of air", although the concepts are not paired in the core framework.

Complexity is related to competency and progressive learning, but complexity and richness does not equate to a continuity of learning. Continuity requires that the same concepts are part of an expanding core framework as learning develops. The evidence of continuity of understanding across the ordered composite maps is seen, for example, in the similar connections in different clusters. Cluster 3 has connections between the concepts "lakes and rivers", "water", "water vapor", "evaporation", "cloud", "rain", and "tiny droplets" that are repeated in cluster 2. The concept "cloud" is enhanced in cluster 2 with relations to "fog", "snow", and "tiny droplets", and includes phase changes and a framework for motion of water through the soil.

A simple test of continuity is the similarity ratio. The similarity measure compares all clusters to the highest ranked cluster 6, looking only at concept pairs having at least 20% occurrence with in the cluster. When the similarity ratios are ordered for similarity to cluster 6, cluster 4, which appears by most structural characteristics to be more complex than clusters 3 and 2, falls in the sequence to the next to last position. Despite its apparent complexity, the concept connections in cluster 4 do not use the same framework as clusters 3, 2, 5, and 7 to build to the knowledge structure represented in cluster 6.

Complex clusters that do not have similarity to one another are possibly organized around a different framework. This dissertation did not pose a question to frame the students' arrangements of the concepts; therefore, different frameworks are even more likely. Furthermore, a characteristic of novice learning (Chi, Feltovich and Glaser, 1981) is the use of alternative frameworks or no particular framework to connect ideas, resulting in redundant and inconsequential relations observed in some clusters.

In Study 4, the less complex maps feature star configurations that radiate to or from a central concept like water instead of relating to one another in a meaningful way. For example, in Cluster 4, "land or soil" connects to "rain", but not to "ground water" or "lakes and rivers" as it does in Cluster 2. Cluster 4 shows "cloud" and "fog" connected to "water", but not to "evaporation" and "water vapor". Cluster 4 has the largest membership of any cluster, and cluster 1, the lowest cluster, has the second largest membership. This finding appears to indicate that a large percentage of each grade level and 39% of all students in Study 4 have produced concept maps that are very low in complexity and consist of few core concepts arranged in a meaningful framework, or students have used alternative connections that do not progress toward the same complex framework. This finding may be influenced one or more of a number of factors: the limited time available for the task, the student's lack of motivation to accomplish the mapping task, interference of the computer-based mapping task itself, and/or the student's level of competency in the domain.

Overall, Part 1 of Study 4 shows evidence of a continuum of expressed understanding of the domain across the ordered composite maps. Part Two of Study 4 explores the relationship of grade level to identifying a continuum of understanding across clusters of similar maps.

When the clusters are ranked in order of increasing complexity, grade twelve students are nearly plateaued across the clusters with a slight rise in cluster 6, the highest in complexity. The percentage of grade nine students peaks in cluster 5, and the percentage for grade six students peaks in the higher rated cluster 7. This finding supports the expectation that learning progresses through the grade levels.

When the percentage of students of each class is charted for each cluster, the trend shows generally higher percentages of six classes in clusters of lower complexity, and higher percentages of grade twelve students in clusters of higher complexity. The pattern is most clearly illustrated by the distribution across clusters of the twelfth grade students in the advanced physics class. This evidence again shows that students' maps are similar to those of other students of the same competency level when maps were clustered by concepts-connected.

For a grade-specific perspective, a composite map is constructed for each grade level showing all concepts-connected at the 30% level of occurrence in the cluster. A wide variation in competency is represented in this student population, as evidenced in the fact that all clusters have members of each grade level. It is not surprising, therefore, that Study 4 does not find a notable difference in the common core of knowledge for student concept maps across grade levels. The wide variation within each grade level and broad overlap between grade level competencies dilutes the differences between grades.

Despite the fact that a significant difference is found between grades six and twelve in the average number of concept pairs per map, the number of unique concept pairs selected by at least 30% of the students is the same for both groups. Evidence shows that the common core of knowledge at the 30% level of agreement for concepts-connected is nearly the same scope for grades six, nine, and twelve. A comparison of composite concept maps of the domain shows three concept pairs common to all three maps, and five concept pairs common to the sixth and twelfth grade maps. There is a slight difference for sixth, ninth, and twelfth grade students' in the cohesiveness of the relationships within composite concept maps of the same domain at the 30% level of agreement in concepts-connected: the sixth grade composite map has a subgroup of two relations; the ninth grade composite map had a subgroup of one relation; the twelfth grade composite map had no subgroups. The 30% level of occurrence of concepts-connected has not been found to discriminate well for evidence of a progression of learning in sixth, ninth, and twelfth grade concept maps of the domain. A comparison of grade-level composites at the 15% level also show subtle differences. The expected higher level connections and process concepts are still missing from all three maps at the 15% level, indicating that very low percentage (if any) students have made those associations in their maps. Students may not have thought deeply enough about the relationships or may not have had sufficient time to process all the concepts and relationships. These comparisons seem to indicate that cross-age clusters of similar maps provide a more fruitful approach than grade level analysis to the identification of a continuum of learning in the domain, since there is evidence of a broad overlap in competency in the domain over the three grade levels, and an exceptional level of competency is not evident in any of the composites. Still, the methodology shows that it is possible to discriminate maps and identify fine differences and continuities in the ways that students represent connections between ideas in the domain.

Educational Implications and Applications

The development of scientific literacy requires that students relate new learning to their framework of prior scientific knowledge and understand the interconnectedness of ideas. The use of language-constrained computer-assisted concept mapping facilitates the analysis of large numbers of concept maps to obtain information about how students collectively see the interconnectedness of ideas within a domain. Teachers can identify what it is that most students know in the context of the domain, and design instruction to build on that knowledge base. For example, the composite concept map for a group of student maps can show the interconnected ideas shared by a large percentage of the students. Alternative conceptions can be recognized and challenged. Missing fundamental concepts and connections can be put in place to ensure understanding of complex ideas, and new learning can be effectively tied to concepts that most students already grasp.

One implication of this dissertation is that a computer-based method of generating and comparing concept maps provides teachers and students with a practical tool for teaching and learning. The software provides a means to rapidly develop concept maps, evaluate objectively the spatial relationships of the concept maps, and generate quantitative data for graphical and statistical analysis. Students may easily develop a concept map by moving concepts and propositions into hierarchical, directed relationships, changing the relationships as needed until they are satisfied that it represents their mental model. The concepts and linking terms provided for the student limit the scope of the knowledge domain to be assessed, limit the cognitive load, and provide a basis for comparisons and statistical analysis of the concept maps that would not be practical without the application of technology.

Ausubel's statement that "...the most important single factor influencing learning is what the learner already knows. Ascertain that and teach him accordingly." charges educators to build on students' prior knowledge. Therefore, a second implication is that the consolidation of groups of similar maps for large numbers of students may be useful in designing instruction to meets the needs of the students. The teacher can bridge from prior knowledge to new learning, and can anchor instruction in known relationships (Smith, diSessa, and Roschelle, 1993; Clement, Brown, and Zeitsman, 1989). The composite map readily shows whether the subsuming concepts are in place, and shows the framework of relations held collectively by the group of students.

A third implication is that students who have experienced a similar curriculum, when given the same toolbox of concepts and linking words, may be expected to construct similar concept maps that provide a means of comparing understanding of a given domain. The methodology in this dissertation retains all connections. The resulting composite incorporates common misconceptions, alternative relationships, and redundant connections, all presented in context. The patterns of interconnections that discriminate levels of understanding among the clusters emerge when the composite maps of the clusters are represented. Consolidating large numbers of concept maps may contribute information to the assessment of the effectiveness of the curriculum: strengths of the curriculum may be inferred from interrelationships shown while weaknesses and gaps in understanding may be implied by patterns of missing ideas and links. Common misconceptions and alternative conceptions are also evident within the interpretative context of the knowledge framework. Looking at these patterns in large numbers of concept maps across grade levels may reveal information that is useful to educators in evaluating and redesigning a curriculum for meaningful learning. If important concepts or connections are largely missing in composite maps, the related learning experiences should be restructured and strengthened, or the sequence of the learning experiences changed to facilitate the understanding of those concepts.

A fourth implication is that this approach can be applied in divergent sectors of the education and business communities for classroom instruction, consensus and building a shared vision, development of systems thinking with a group, or clustering of consumer preferences. Advances in computer-assisted concept mapping and analysis make concept mapping a more widely useful tool for learning and probing understanding of complex domains.

Limitations

Computer Skills

Although students can quickly implement concept mapping with paper and pencil, the computer-assisted concept mapping facilitates the mapping process. Students learn the software in minutes, but facility with the mouse is of some concern. The current version of the software requires the user to click one way on the concept to move the concept in the map, and to click another way to connect two concepts. This characteristic of the software tool requires more practice for some students to master, and may be a contributing factor in limiting the size of the map that some students were able to produce in the time available.

Time Constraints

The maps in this dissertation were constructed in a typical classroom environment during a normal class period during which the students also received brief instruction in concept mapping and use of the computer program. Time constraints did not permit an opportunity for students to re-visit their maps to complete them if left unfinished at the end of the class period. In a more favorable situation, instruction in concept mapping and use of the program may be done during another class period, and students could be given more time to concentrate on relations in their maps. Maps that were not completed due to lack of time may contribute to the 39% of students' maps that cluster in two groups that have characteristics of lower complexity and represent limited understanding.

Concept Mapping Strategies

Concept mapping techniques can take considerable time to learn. When confronted with a long list of complexly related terms, inexperienced and less able students will have particular difficulty with the mapping task. Even experts can be challenged. Difficulties with the task can cloud the results. Students participating in the four studies in this dissertation had prior experience with some types of semantic mapping, although not necessarily concept mapping. CCM does not require hierarchical concept mapping, but certainly students should be able to produce better maps if they are more experienced in the technique.

Although this method of constructing concept maps is especially designed for the evaluation of large numbers of students that would preclude the use of interviews, there is no denying that a follow up interview with each student, when possible, provides a richer view of what she understands.

Constrained Concepts and Linking Phrases

Although no direct evidence was collected from the four studies, it is important to reiterate the discussion in Chapter Two on language-constraints. Language constraints have the benefit of allowing direct comparisons between concept maps since they are constructed with the same building blocks. Limitations, however, accrue from 1) the provided concepts, 2) linking words, and 3) the language-constrained mapping task itself. First, students bring different perspectives to the same domain, based on their prior experiences and related learning. The set of concepts provided may not accommodate the needs of a student who has an alternative, but viable, view of the domain that includes complex interconnections between provided concepts and other ideas. Language constraints limit the range and depth of concepts, and the mapping task may, as a consequence, under-estimate student understanding. Second, provided linking words that differ from the common language of the student may be misinterpreted and used inappropriately to describe relations between concepts. Furthermore, even when there is agreement that two concepts are connected, different phrases are used by different students to describe the relationship. Third, when construction elements are provided for the computer-assisted mapping task, an unmotivated student can easily arrange the provided concepts in a web of random words, providing yet another way for the mapping task itself to interfere. Further limitations of language-constrained concept mapping specific to the four studies of this dissertation are discussed in the following sections.

Selection of Concepts and Linking Phrases

The specific concepts and linking phrases and the number of concepts and linking phrases are important considerations. This dissertation used thirty concepts and ten linking phrases to accommodate a broader scope of understanding of the domain. The number of concepts may have been too many for students to deeply consider in the time available for the mapping task. The number of linking phrases may also have been too many to consider if one approaches the task as multiple choice.

Although the specific concepts were taken from the curriculum outline, what is not certain is the extent to which these concepts were specifically taught in the classrooms of student participants. The mapping task was done at the end of the school year when the sixth grade students were about to begin a formal study of the water cycle. The ninth grade students had recently completed a study of water erosion in a geology unit. Students in the tenth through twelfth grade probably do not receive direct instruction about the water cycle, although processes relating to the water cycle are embedded in biology, chemistry, and physics units. The ideas represented by most students may be the result of indirect instruction and naive conceptions as opposed to formal learning about the water cycle.

An anomaly in the concept set was the introduction of some verbs as concepts. In this case, it was not imperative, although it was desirable, to use a linking phrase to connect to another concept. To avoid this dilemma, concepts should be nouns; otherwise, a "blank" linking phrase is needed for cases where the student elects not to use any of the available links.

Selection of linking phrases can also create problem relations. For example, a phrase such as "into/in" does not include a verb and therefore opens up the possibility that the student will use the link to create a complete statement including a string of three or more concepts. These long strings of concepts and linking terms make sense when used altogether, however, the method of analysis used in this dissertation dissects the maps into concept-link-concept triads, and taken out of the context of the meaningful string, the excerpted triad may appear to be incorrect or nonsensical. For the concept mapping task, for example, some students used the phrase "into" instead of the phrase "rises into" or even in place of "produces/forms".

Another important consideration is that linking phrases consist of simple, basic relations such as Danssereau and Holly (1982) prescribe. The similarity measures for linking phrases may have been higher had the number of linking phrases been limited to fewer choices. The rationale for the inclusion of ten linking phrases was to allow for differences in choice that might relate to the student's competency level, a subject for further research. Although some problems derive from language constraints, advantages accrue with the ease with which maps can be revised, the diminishing of the student's cognitive load during the task, and the ease with maps may be compared and clustered for analysis.

For this dissertation, similarity measures for choice of linking phrases, and directionality of the links were low, indicating that even when students connected the same concepts, they often chose different linking phrases from the range provided. Because the similarity ratios for linking phrases were low, this dissertation does not report the characteristics or pursue the analysis further.

Directionality of Relations

Similarity ratios for directionality were correspondingly low since the layers of similarity are compounded in the comparison. Linking phrases were selected for the domain so that opposites would not confound the comparison. In other words, the phrases "produces/forms" and "is a cause of" were included in the list of provided linking phrases, while avoiding "is produced by" or "is the effect of". Low similarities for directionality or full congruence between concept maps is expected to correspond to the choice of linking phrases which determine the hierarchical direction of the statement. In addition, students make occasional mistakes in drawing the connection between two concepts, and the direction is opposite what they might intend. This could be avoided with careful checking. For this mapping task, students may not have had time to check all relations, and this was their first experience with CCM.

Further Studies

This method has been used in one school district with students in grades six, nine, and twelve. Further research is needed with students at different grade levels and of different backgrounds; additional research is needed using other domains, other disciplines, and other sets of language-constrained concepts and linking phrases to test the generalizability of this dissertation. A longitudinal study is needed to follow the development of understanding of a group of students as they progress through the curriculum. Research is needed to see if the power of the analysis can discriminate maps and levels of understanding at the greater depth of linking phrases and directionality.

Further studies should determine whether the use of these tools to reveal ways that students believe concepts to be related can ameliorate actual classroom instruction and contribute insights to curriculum evaluation and revision.

The value of other referents such as experts' or teachers' maps for the comparison of student maps should be explored, and further studies are needed to develop the use of the "test point" analysis. A small test set of interconnected concepts could prove useful in representing for a class each student's understanding of a specific idea. Multi-dimensional scaling may be used to show the proximity of the student map to the test point. The graphical representation of MDS would provide a means to evaluate which students have acquired the essential learning and which have not.

Improvements to the CCM software may benefit future research. Although the current version of the CCM software is functional, enhancements are desirable. The Knot-Mac software was functional in this dissertation; however, the analysis would benefit from the development of a tool for the graphical representation of composite maps from adjacency matrices that could, for example, show the strength of relations with lines of varying thickness keyed to the percentage occurrence, and colors keyed to linking phrases.

Conclusion

Students who have experienced a similar curriculum, when given the same toolbox of concepts and linking words, may be expected to construct similar concept maps that provide a means of comparing understanding of a given domain. To use concept mapping more effectively as a means of probing student understanding, more powerful tools are needed to see how students identify relationships. Tools are needed which not only make it easier for the teacher, but also provide insights that laborious hand analysis would prevent. This dissertation demonstrates that language-constrained computer-assisted concept mapping can be a valid and reliable alternative to traditional concept mapping, and provides insights to how Pathfinder analysis can be extended to the comparison of the structural features of student concept maps to identify similar concept maps, discriminate levels of student understanding, find evidence of a progression of understanding, and identify a common core of knowledge for groups of students.

This dissertation has shown that language-constrained computer-assisted concept mapping, in which students use provided lists of concepts and linking words, is a valid means of producing student generated concept maps. This dissertation has also demonstrated that the application of technology makes it possible to discriminate for large numbers of students as well as pairs of students on concept maps and to easily identify clusters of similar maps. It is possible to identify a continuum of learning by identifying a continuity of knowledge represented in concept maps and to identify other characteristics of concept map clusters which signify a progression in the complexity of relationships in the domain. This dissertation has demonstrated that it is possible to create a composite concept map of relationships representing the core framework for a domain for a student population. As important is the ease to which relations between concepts are highlighted and presented in clear graphical patterns and in the context of the knowledge framework.

APPENDICES

APPENDIX A

SAMPLE CONSENT FORM

PERMISSION TO PARTICIPATE IN A RESEARCH STUDY
Students' Concept Patterns Revealed by Computer Analysis of Language-Constrained Science Concept Maps

Your student is invited to participate in a University of Michigan dissertation research study. Participating students in grades six, nine and twelve will use paper and pencil and a computer program to show how they think a set of science concepts are related. Students will use a Windows program in which they will move and arrange concepts and linking words, connecting them to show relationships. The purpose of the study is to find patterns in the way students who have had different experiences and developed different knowledge connect ideas. The study will identify groups of similar concept maps and examine whether patterns in these groups of maps show evidence of a growth of understanding.

Your student will not be identified in the study. The maps that your student produces will be assigned a code to identify the grade level and class. Your student will not be graded on performance.

Some students at each grade level will be asked to do a "think-aloud" as they connect the concept and linking words in the computer program. This will help us understand the thought process and decisions the student makes while using the program. The "think-aloud" will be taped, but the student will not be identified and no personal information will be recorded. The tape will be used solely for diagnostic purposes of the program.The tape will be destroyed when the research is complete.

One or two science class periods are needed for the study. Participation is this study is completely voluntary. Your student may withdraw from the study at any time. Classes of particpants will be divided into groups, with some students doing alternative class assignments while other students go to the computer lab for the study. Students who do not participate in the research study will not be readily identified by their classmates.

If you have further questions about this research study, please contact Barbara Fife.
at 810-344-8111 or by e-mail: fifeb@nhs.northville.k12.mi.us

________________________________ may participate. Yes ___ No___
Student Name

My student is comfortable using Windows programs and the mouse. Yes ___ No___

My student has permission to do a "think-aloud" as part of the study. Yes ___ No___

________________________ ________________________
School Grade/ Teacher

Comments ____

____

________________________ ________________________
Parent/Guardian Signature Date

APPENDIX B

MATERIALS USED FOR THE CONCEPT MAPPING TASKS

The pizza concept map was used in Study 1 and Study 2 to test the validity and reliability of language-constrained concept mapping. The same set of concepts and links were used for the introductory concept mapping lesson in Study 3. Figure B1 shows the design of the transparency and worksheets used for Study 3. The computer-based task used the same format and order of concepts and linking phrases.

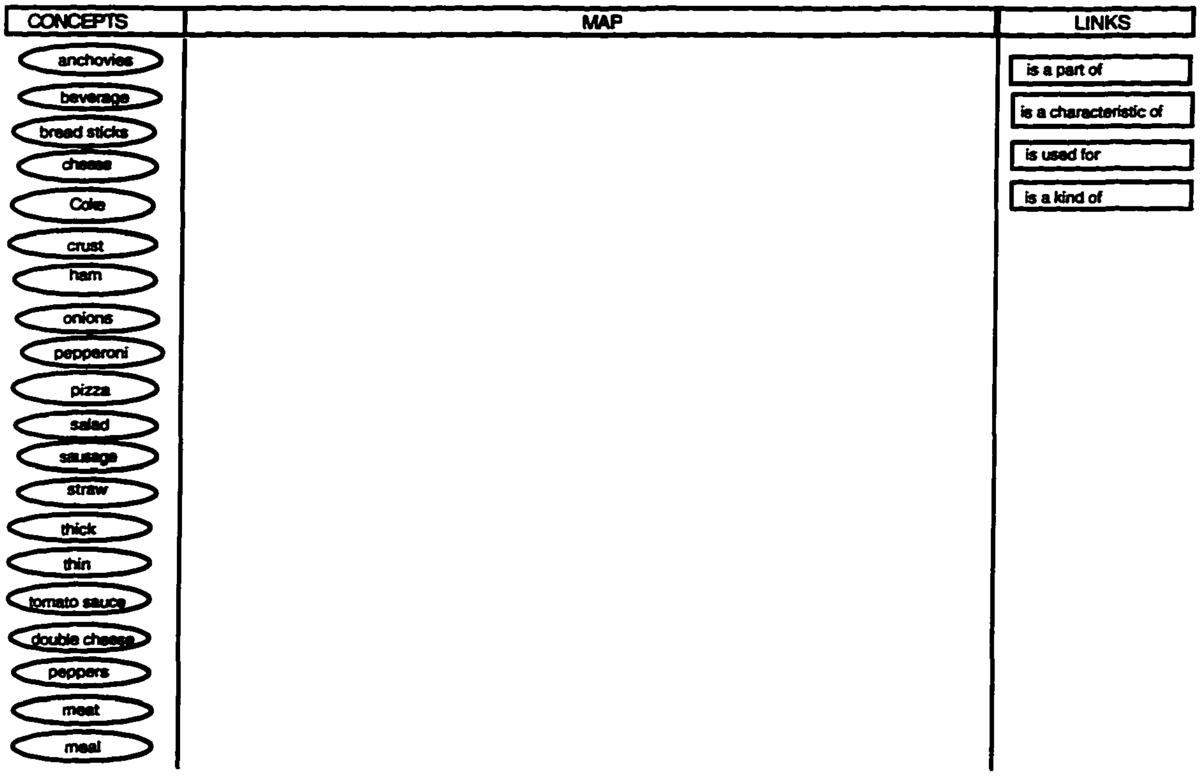

Figure B1. Sample of the pizza worksheet reduced from original size.

Table B1.

Water Cycle Concepts and Linking Phrases Provided in the Language-constrained Concept Mapping Tasks. Corresponding Numbers and Letters Are Used to Encode the Map Output as Triadic Relations.

	Concepts		Linking Phrases
1	water	a	is/are
2	water vapor	b	produces/forms
3	lakes and rivers	c	is a cause of
4	ground water	d	has effect-increases
5	atmosphere	e	has effect-decreases
6	land or soil	f	rises into
7	season & climate	g	falls on
8	precipitation	h	into/on
9	respiration	i	releases heat energy
10	transpiration	j	absorbs heat energy
11	evaporation		
12	combustion		
13	infiltrates		
14	condenses		
15	melts		
16	freezes		
17	dust/air pollution		
18	run off		
19	separate molecules		
20	tiny droplets		
21	invisible		
22	visible		
23	cloud		
24	snow		
25	ice		
26	rain		
27	frost		
28	fog		
29	density of air		
30	atmospheric pressure		

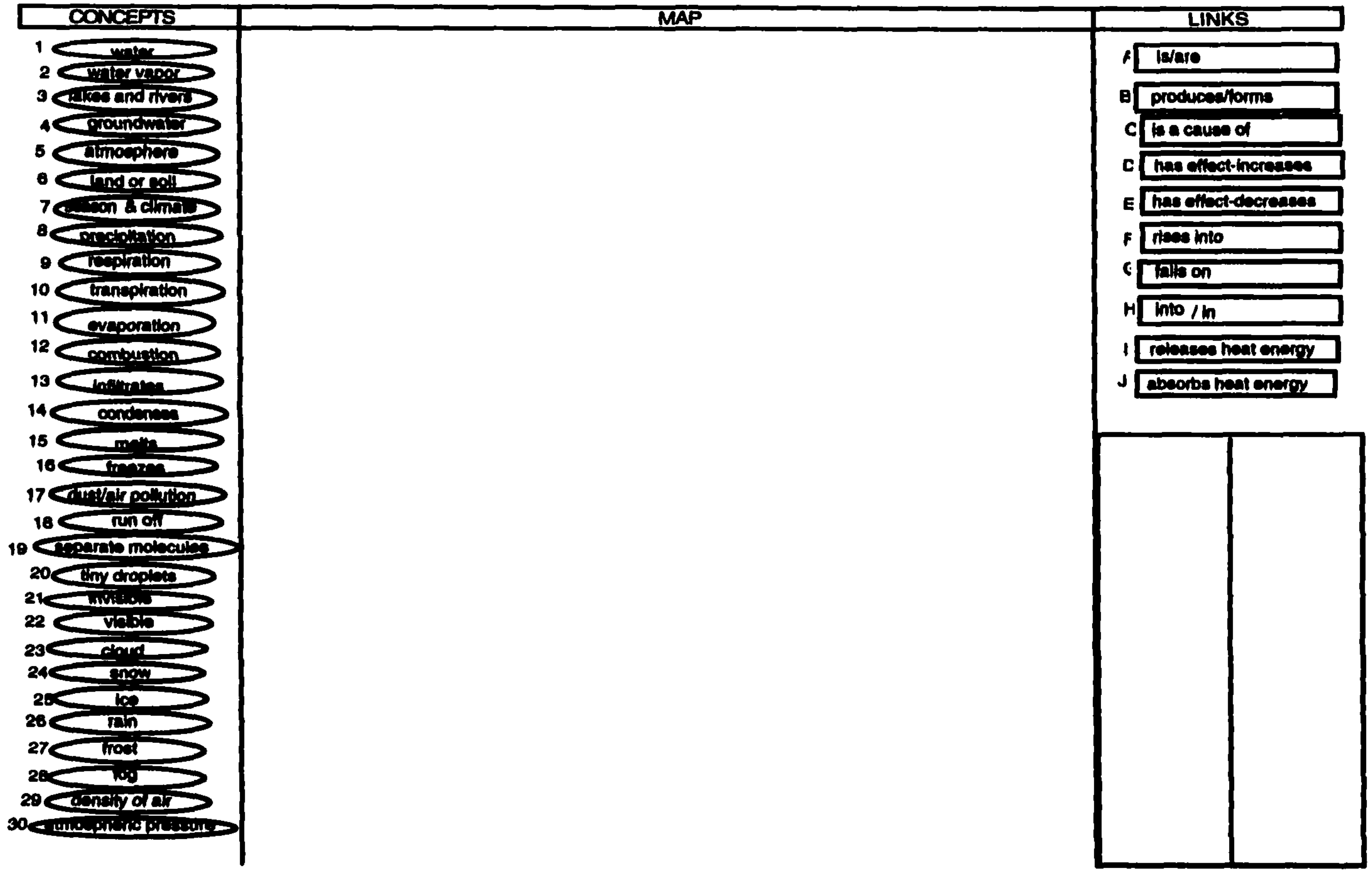

Figure B2. Sample water cycle worksheet reduced from original size.

Sample Instructions for the Pencil and Paper Concept Mapping Task

Please look at the entire list of concepts on the left. You are to link these ideas as you see them related. You may begin your map with any one of the concepts in the list. I would suggest that you start your first concept an inch or two from the top of the map area in case you decide later to add more links to that concept. That way you will have enough space to arrange your map.

Please draw an oval and write the concept inside, then draw the next concept that you want to link to it. Say in your mind the relation between the two concepts and then draw the connecting arrow beginning with the first concept and ending with the second as we did for the pizza map. Remember to draw the arrow head so that it points toward the last concept in your statement.

To save time and avoid writing so much you may label the arrows with letters to represent the linking words instead of writing out the entire phrase; however, you really need to write out the concepts. That will make it easier for you to find them when adding concepts to your map.

You may use as many of the thirty concepts as you wish, but use only those concepts or links that you understand and that have some meaning for you. If you are not familiar with a term, do not use it in your map.

Each linking phrase may be used as many times as you need it in the map. You may draw from any one concept as many links to other concepts as you wish, but you may draw each concept on the map only once.

All concepts used in the map are to be linked together. You should not have separate little groups of concepts.

When you are trying to choose the best linking phrase you may find that the given tense or ending of the concept or link does not fit well in your statement. If absolutely necessary you may imagine the ending to be changed. If a link cannot be found or is absolutely not needed for the relation you may leave it blank in the paper exercise. This should be a rare exception.

Features of the Computer-assisted Concept Mapping Software (CCM)

1. CCM provides pre-determined concepts entered by the instructor. Each concept is shown in an oval. The vertical concept list appears in a window on the left side of the monitor screen. Within the computer program each concept is identified by its original numerical order in the sequence (1,2,...n).
2. CCM provides ten or fewer linking propositions, entered by the instructor, each in a rectangle. The Link Corral appears in a window on the right side of the monitor screen. All icons of linking phrases are treated as stacks. Each linking proposition is identified internally in the program by its alphabetic position in the sequence (A,...J)
3. Students select a concept by clicking on a concept and dragging it to the new location in the central map window of the screen. Concepts are linked by clicking at the center of the first concept and dragging the mouse pointer to the center of the second concept of the pair. A directional arrow then joins the two concepts, pointing to the second concept. An empty rectangle to be filled with a linking phrase appears on the arrow. Concepts may be used only once and disappear from the list of available concepts when they have been moved to the map window.
4. Students select a linking proposition from the link corral by clicking and dragging it to the empty rectangle between two concepts in the map window of the display. Propositions have unlimited availability. When one is moved from the link corral, it is replaced by an identical linking proposition in the stack.
5. The direction of the arrow follows the direction of the mouse cursor movement. Links (arrows) may be deleted by clicking on the arrow and pressing delete.
6. If nodes (concepts) are moved (by clicking and dragging the edge of the icon to a new location) each node remains connected by its original links.

7. **When the student saves the map, a coded text output file consisting of all relations or concept-link-concept triads within the student map is automatically generated by the computer program. The coded output identifies concepts by number and linking phrases by letters, e.g. 3B10, with one triad per line.**

APPENDIX C

Table C1

Study 1: Comparison of Relations in the Pencil and Paper and Computer-Assisted Language-Constrained Concept Map Constructions of Twelve Students

		Similarity Measures			Concept Triads			
Student	Grade	Concepts Connected	Same Links	Same Direction	Match	Different Link	Different Direction	No Match
A	6	0.818	0.429		12	3	3	4
B	6	0.500	0.364		5	1	1	12
C	6	0.438	0.353		9	1	0	20
D	6	0.393	0.258		6	3	1	19
E	9	0.500	0.312		10	4	1	13
F	9	0.739	0.481		13	4	0	6
G	9	0.696	0.625		15	1	0	7
H	9	0.750	0.312		5	6	7	6
I	12	0.947	0.947		18	0	0	1
J	12	0.611	0.450		9	2	0	7
K	12	0.667	0.400		10	4	0	7
L	12	0.900	0.900		18	0	0	2
Average		0.663	0.486		10.83	2.42	1.08	8.67

APPENDIX D

Table D1

Similarity Ratios for Concepts Used in CCM Concept Maps Constructed by Fifteen Sixth Grade Students in Two Sessions One Week Apart in Study 2.

	Session II														
Session I	AAA	BBB	CCC	DDD	EEE	FFF	GGG	HHH	III	JJJ	KKK	LLL	MMM	NNN	PPP
AAA	**0.421**	0.400	0.400	0.353	0.400	0.421	0.400	0.400	0.400	0.400	0.400	0.400	0.400	0.400	0.350
BBB	0.950	**1.000**	1.000	0.750	1.000	0.950	0.650	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.950
CCC	0.263	0.250	**0.250**	0.250	0.250	0.263	0.385	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.263
DDD	0.263	0.250	0.250	**0.333**	0.250	0.263	0.286	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.263
EEE	0.632	0.600	0.600	0.688	**0.600**	0.550	0.389	0.600	0.600	0.600	0.600	0.600	0.600	0.600	0.632
FFF	0.250	0.300	0.300	0.312	0.300	**0.316**	0.267	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.316
GGG	0.368	0.350	0.350	0.375	0.350	0.368	**0.538**	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.300
HHH	0.632	0.600	0.600	0.688	0.600	0.632	0.471	**0.600**	0.600	0.600	0.600	0.600	0.600	0.600	0.632
III	0.850	0.900	0.900	0.650	0.900	0.850	0.550	0.900	**0.900**	0.900	0.900	0.900	0.900	0.900	0.850
JJJ	0.474	0.450	0.450	0.412	0.450	0.474	0.571	0.450	0.450	**0.450**	0.450	0.450	0.450	0.450	0.400
KKK	0.526	0.500	0.500	0.667	0.500	0.526	0.438	0.500	0.500	0.500	**0.500**	0.500	0.500	0.500	0.526
LLL	0.895	0.850	0.850	0.778	0.850	0.800	0.500	0.850	0.850	0.850	0.850	**0.850**	0.850	0.850	0.800
MMM	0.737	0.700	0.700	0.706	0.700	0.737	0.500	0.700	0.700	0.700	0.700	0.700	**0.700**	0.700	0.650
NNN	0.579	0.550	0.550	0.625	0.550	0.579	0.412	0.550	0.550	0.550	0.550	0.550	0.550	**0.550**	0.579
PPP	0.400	0.450	0.450	0.500	0.450	0.474	0.467	0.450	0.450	0.450	0.450	0.450	0.450	0.450	**0.474**

Table D2

Similarity Ratios for Concepts Connected in CCM Concept Maps Constructed by Fifteen Sixth Grade Students in Two Sessions One Week Apart in Study 2.

	Session II														
Session I	AAA	BBB	CCC	DDD	EEE	FFF	GGG	HHH	III	JJJ	KKK	LLL	MMM	NNN	PPP
AAA	**0.316**	0.238	0.238	0.158	0.130	0.190	0.111	0.130	0.300	0.034	0.182	0.083	0.300	0.227	0.190
BBB	0.538	**0.414**	0.640	0.321	0.414	0.429	0.346	0.206	0.414	0.154	0.367	0.206	0.577	0.556	0.379
CCC	0.158	0.211	**0.150**	0.188	0.211	0.158	0.308	0.150	0.211	0.038	0.211	0.095	0.211	0.200	0.158
DDD	0.100	0.150	0.095	**0.188**	0.150	0.100	0.214	0.045	0.095	0.038	0.150	0.095	0.095	0.200	0.222
EEE	0.474	0.208	0.381	0.316	**0.381**	0.273	0.353	0.261	0.381	0.179	0.318	0.208	0.381	0.364	0.333
FFF	0.211	0.200	0.200	0.250	0.200	**0.278**	0.200	0.143	0.263	0.077	0.263	0.200	0.263	0.136	0.211
GGG	0.200	0.136	0.190	0.312	0.316	0.200	**0.462**	0.136	0.136	0.074	0.190	0.136	0.190	0.300	0.263
HHH	0.261	0.250	0.250	0.300	0.304	0.261	0.333	**0.250**	0.200	0.172	0.250	0.154	0.364	0.348	0.450
III	0.591	0.500	0.565	0.455	0.500	0.591	0.364	0.333	**0.636**	0.212	0.636	0.333	0.714	0.609	0.458
JJJ	0.227	0.120	0.217	0.263	0.217	0.227	0.158	0.120	0.167	**0.067**	0.217	0.167	0.167	0.208	0.227
KKK	0.286	0.333	0.273	0.412	0.333	0.286	0.294	0.120	0.333	0.067	**0.273**	0.167	0.273	0.261	0.227
LLL	0.360	0.129	0.346	0.348	0.522	0.308	0.261	0.207	0.296	0.182	0.296	**0.458**	0.250	0.333	0.259
MMM	0.476	0.333	0.455	0.556	0.391	0.476	0.238	0.231	0.391	0.125	0.600	0.280	**0.455**	0.500	0.409
NNN	0.400	0.318	0.450	0.471	0.450	0.474	0.278	0.208	0.381	0.100	0.526	0.318	0.450	**0.429**	0.400
PPP	0.182	0.174	0.174	0.278	0.227	0.238	0.312	0.125	0.125	0.107	0.227	0.125	0.227	0.273	**0.368**

Table D3

Similarity Ratios for Concepts Connected with the Same Linking Phrases in CCM Concept Maps Constructed by Fifteen Sixth Grade Students in Two Sessions One Week Apart in Study 2.

	Session II														
Session I	AAA	BBB	CCC	DDD	EEE	FFF	GGG	HHH	III	JJJ	KKK	LLL	MMM	NNN	PPP
AAA	**0.190**	0.130	0.083	0.048	0.040	0.087	0.053	0.130	0.182	0.034	0.083	0.040	0.040	0.125	0.042
BBB	0.379	**0.242**	0.139	0.121	0.108	0.250	0.167	0.079	0.281	0.098	0.242	0.079	0.139	0.400	0.250
CCC	0.100	0.000	**0.095**	0.118	0.095	0.100	0.133	0.000	0.095	0.000	0.150	0.045	0.095	0.143	0.100
DDD	0.100	0.045	0.045	**0.118**	0.095	0.100	0.214	0.045	0.045	0.038	0.045	0.095	0.000	0.043	0.000
EEE	0.217	0.036	0.115	0.136	**0.074**	0.120	0.150	0.036	0.208	0.031	0.160	0.074	0.208	0.154	0.120
FFF	0.095	0.000	0.143	0.176	0.091	**0.150**	0.059	0.091	0.200	0.037	0.200	0.000	0.200	0.136	0.150
GGG	0.091	0.000	0.136	0.050	0.042	0.043	**0.267**	0.000	0.136	0.036	0.087	0.087	0.042	0.083	0.043
HHH	0.074	0.071	0.154	0.083	0.111	0.074	0.000	**0.111**	0.111	0.062	0.154	0.000	0.111	0.292	0.381
III	0.296	0.059	0.161	0.231	0.125	0.207	0.034	0.091	**0.500**	0.111	0.500	0.000	0.161	0.423	0.346
JJJ	0.080	0.037	0.120	0.043	0.037	0.080	0.100	0.037	0.077	**0.032**	0.077	0.120	0.077	0.115	0.080
KKK	0.080	0.037	0.077	0.091	0.037	0.080	0.048	0.037	0.167	0.032	**0.167**	0.000	0.120	0.208	0.174
LLL	0.062	0.094	0.207	0.000	0.029	0.062	0.208	0.029	0.061	0.083	0.029	**0.250**	0.061	0.091	0.062
MMM	0.240	0.185	0.185	0.167	0.067	0.192	0.040	0.103	0.231	0.091	0.280	0.032	**0.333**	0.179	0.148
NNN	0.333	0.074	0.160	0.190	0.160	0.273	0.150	0.036	0.208	0.065	0.381	0.074	0.261	**0.364**	0.273
PPP	0.040	0.038	0.080	0.045	0.080	0.040	0.000	0.038	0.125	0.033	0.227	0.000	0.038	0.273	**0.368**

Table D4

Similarity Ratios for Concepts Connected with the Same Linking Phrases and Directionality of Links in CCM Concept Maps Constructed by Fifteen Sixth Grade Students in Two Sessions One Week Apart in Study 2.

	Session II														
Session I	AAA	BBB	CCC	DDD	EEE	FFF	GGG	HHH	III	JJJ	KKK	LLL	MMM	NNN	PPP
AAA	**0.136**	0.130	0.040	0.048	0.040	0.087	0.053	0.130	0.182	0.034	0.083	0.040	0.040	0.125	0.042
BBB	0.290	**0.242**	0.079	0.121	0.108	0.212	0.167	0.079	0.281	0.098	0.242	0.079	0.139	0.400	0.212
CCC	0.048	0.000	**0.045**	0.056	0.045	0.048	0.062	0.000	0.045	0.000	0.045	0.000	0.095	0.091	0.100
DDD	0.100	0.045	0.000	**0.118**	0.095	0.100	0.133	0.045	0.045	0.000	0.045	0.095	0.000	0.043	0.000
EEE	0.217	0.036	0.036	0.136	**0.074**	0.120	0.150	0.036	0.208	0.031	0.115	0.074	0.208	0.154	0.120
FFF	0.095	0.000	0.043	0.176	0.091	**0.150**	0.059	0.091	0.200	0.037	0.143	0.000	0.200	0.136	0.150
GGG	0.091	0.000	0.042	0.050	0.042	0.043	**0.267**	0.000	0.136	0.036	0.042	0.087	0.042	0.083	0.043
HHH	0.036	0.071	0.034	0.040	0.071	0.036	0.000	**0.071**	0.071	0.030	0.071	0.000	0.071	0.240	0.318
III	0.207	0.059	0.059	0.231	0.125	0.207	0.034	0.091	**0.500**	0.111	0.440	0.000	0.161	0.423	0.346
JJJ	0.080	0.037	0.000	0.043	0.037	0.080	0.100	0.037	0.077	**0.032**	0.037	0.120	0.077	0.115	0.080
KKK	0.080	0.037	0.037	0.091	0.037	0.080	0.048	0.037	0.167	0.032	**0.120**	0.000	0.120	0.208	0.174
LLL	0.061	0.091	0.091	0.000	0.029	0.061	0.200	0.029	0.059	0.053	0.000	**0.241**	0.059	0.088	0.061
MMM	0.148	0.185	0.103	0.167	0.067	0.192	0.040	0.103	0.231	0.091	0.231	0.032	**0.333**	0.179	0.148
NNN	0.333	0.074	0.074	0.190	0.160	0.273	0.150	0.036	0.208	0.065	0.318	0.074	0.261	**0.364**	0.273
PPP	0.040	0.038	0.000	0.045	0.080	0.040	0.000	0.038	0.125	0.033	0.174	0.000	0.038	0.273	**0.368**

APPENDIX E

Table E1.

Occurrence of Concept Pairs for Each Grade Level Ranked by Percent Occurrence in Grade 9 Students' Language-constrained Computer-assisted Concept Maps in Study 3.

Concept	Pair	%12	Rank	%9	Rank	%6	Rank
water	lakes and rivers	54.8	1	51.7	1	48.5	1
precipitation	rain	49.2	2	50	2	39.7	3
water	water vapor	46.8	3	46.6	3	46.1	2
water	ground water	22.6	13	41..4	4	20.1	15
water	rain	21.8	14	36.2	5	33.8	7
water	precipitation	29.8	10	32.8	6	15.7	22
freezes	ice	41.1	4	29.3	7	35.8	5
precipitation	snow	31.5	9	29.3	7	19.1	16
lakes and rivers	run off	16.9	21	29.3	7	12.7	26
water vapor	evaporation	37.9	6	27.6	8	38.2	4
water	ice	32.3	8	27.6	8	27.5	11
tiny droplets	rain	21	15	27.6	8	35.8	5
water vapor	invisible	18.5	19	27.6	8	26	13
water vapor	cloud	20.2	16	25.9	9	35.3	6
ground water	land or soil	13.7	25	25.9	9	12.7	26
melts	ice	38.7	5	24.1	10	30.9	9
land & soil	rain	31.5	9	24.1	10	25.5	14
cloud	fog	16.9	21	24.1	10	27	12
water	land or soil	11.3	28	24.1	10	10.8	29
water	freezes	33.1	7	22.4	11	26	13
water	evaporation	27.4	11	22.4	11	32.4	8
melts	snow	21	15	20.7	12	17.2	19
freezes	snow	19.4	17	20.7	12	16.7	20
ground water	run off	15.3	23	20.7	12	3.4	43

Table E1 (continued)

Concept	Pair	%12	Rank	%9	Rank	%6	Rank
land & soil	run off	12.9	26	20.7	12	7.8	34
precipitation	cloud	16.1	22	19	13	13.2	25
lakes and rivers	rain	14.5	24	17.2	14	18.6	17
run off	rain	10.5	29	17.2	14	2.5	45
water	run off	4.8	36	17.2	14	5.4	39
cloud	rain	24.2	12	15.5	15	28.4	10
water vapor	fog	17.7	20	15.5	15	10.3	30
freezes	frost	16.1	22	15.5	15	7.8	34
atmosphere	dust/air pollution	15.3	23	15.5	15	8.3	33
visible	cloud	12.1	27	15.5	15	9.8	31
snow	ice	8.9	31	15.5	15	11.8	27
water	snow	19.4	18	13.8	16	18.6	17
density of air	atmospheric	16.1	22	13.8	17	8.3	33
water	melts	12.9	26	13.8	17	18.6	17
land & soil	precipitation	11.3	28	13.8	17	8.8	32
atmosphere	cloud	8.1	32	13.8	17	13.7	24
precipitation	evaporation	8.1	32	13.8	17	6.4	37
water vapor	atmosphere	18.5	19	12.1	18	10.3	30
tiny droplets	fog	11.3	28	12.1	18	1.5	47
tiny droplets	cloud	10.5	29	12.1	18	10.8	29
cloud	snow	8.1	32	12.1	18	13.2	25
atmosphere	atmospheric	8.1	32	12.1	18	8.8	32
ground water	rain	8.1	32	12.1	18	6.4	37
lakes and rivers	evaporation	8.1	32	12.1	18	5.4	39
snow	frost	6.5	34	12.1	18	10.8	29
water vapor	rain	4.8	36	12.1	18	6.4	37
lakes and rivers	ground water	24.2	12	10.3	19	15.7	22
water vapor	tiny droplets	21.8	14	10.3	19	11.8	27
atmosphere	season & climate	16.1	22	10.3	19	7.4	35
water vapor	condenses	12.9	26	10.3	19	7.4	35

Table E1 (continued)

Concept	Pair	%12	Rank	%9	Rank	%6	Rank
evaporation	cloud	11.3	28	10.3	19	14.7	23
separate molecules	tiny droplets	9.7	30	10.3	19	2.9	44
lakes and rivers	precipitation	8.1	32	10.3	19	6.4	37
water	cloud	4.8	36	10.3	19	16.2	21
precipitation	ice	4.8	36	10.3	19	3.9	42
water vapor	transpiration	4	37	10.3	19	0.5	49
water	atmosphere	12.1	27	8.6	20	8.8	32
season & climate	precipitation	11.3	28	8.6	20	3.9	42
water	frost	10.5	29	8.6	20	8.3	33
visible	fog	8.1	32	8.6	20	7.8	34
snow	rain	8.1	32	8.6	20	4.4	41
precipitation	visible	5.6	35	8.6	20	2	46
precipitation	tiny droplets	14.5	24	6.9	21	4.4	41
freezes	rain	10.5	29	6.9	21	10.3	30
fog	density of air	10.5	29	6.9	21	3.4	43
ice	rain	8.1	32	6.9	21	7.8	34
land & soil	snow	8.1	32	6.9	21	6.9	36
atmosphere	evaporation	7.3	33	6.9	21	6.9	36
condenses	cloud	6.5	34	6.9	21	10.3	30
visible	rain	6.5	34	6.9	21	7.4	35
ground water	precipitation	6.5	34	6.9	21	1	48
water vapor	frost	5.6	35	6.9	21	1.5	47
season & climate	snow	4.8	36	6.9	21	6.4	37
melts	run off	4.8	36	6.9	21	3.4	43
tiny droplets	frost	4	37	6.9	21	1	48
water vapor	lakes and rivers	3.2	38	6.9	21	6.9	36
dust/air pollution	atmospheric	2.4	39	6.9	21	0.5	49
precipitation	frost	1.6	40	6.9	21	2.9	44
water	visible	14.5	24	5.2	22	17.6	18
evaporation	invisible	12.1	27	5.2	22	13.2	25

Table E1 (continued)

Concept	Pair	%12	Rank	%9	Rank	%6	Rank
water vapor	precipitation	9.7	30	5.2	22	4.4	41
ice	frost	8.1	32	5.2	22	7.4	35
precipitation	condenses	8.1	32	5.2	22	2.5	45
separate molecules	invisible	8.1	32	5.2	22	2.5	45
precipitation	run off	6.5	34	5.2	22	1	48

APPENDIX F

Table F1

<u>Percentage Occurrence of Concepts for Same-Concept Clusters Ranked by Range</u>

Concept	Concept	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8	Cluster 9	Range
30	atmospheric pressure	3.8	19	4.5	7.9	63	100	35	0	1.4	100.00
5	atmosphere	15	65	0	39	91	97	68	26	19	97.00
29	density of air	3.8	39	0	16	75	97	40	2.9	4.1	97.00
28	fog	3.8	58	27	39	91	100	84	77	53	96.20
16	freezes	23	42	86	5.3	96	64	70	5.7	88	90.70
15	melts	27	45	91	11	95	61	63	5.7	82	89.30
19	separate molecules	3.8	9.7	4.5	7.9	53	91	9.5	2.9	2.7	88.30
17	dust/air pollution	7.7	48	9.1	13	54	94	30	8.6	8.1	86.30
27	frost	7.7	39	23	42	86	94	68	29	47	86.30
18	run off	12	48	23	16	74	97	52	26	34	85.00
21	invisible	15	29	27	32	84	100	60	51	26	85.00
22	visible	15	39	18	34	91	100	67	69	24	85.00
7	season & climate	19	52	4.5	2.6	75	85	37	8.6	20	82.40
8	precipitation	35	45	18	53	88	100	87	80	69	82.00
23	cloud	27	65	36	68	98	100	90	97	92	73.00

Table F1 (continued)

Percentage Occurrence of Concepts for Same-Concept Clusters Ranked by Range

Concept	Concept	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8	Cluster 9	Range
25	ice	27	61	77	53	98	94	95	83	96	71.00
9	respiration	12	9.7	0	2.6	19	70	6.3	0	4.1	70.00
12	combustion	0	16	4.5	2.6	11	70	6.3	0	0	70.00
20	tiny droplets	31	68	45	42	91	100	70	71	72	69.00
4	ground water	38	55	41	39	86	100	68	49	57	62.00
14	condenses	27	35	9.1	7.9	47	67	40	5.7	22	61.30
6	land or soil	42	81	41	45	98	94	76	86	51	57.00
2	water vapor	50	71	41	74	96	94	92	97	80	56.00
10	transpiration	3.8	6.5	4.5	11	14	58	14	2.9	5.4	55.10
13	infiltrates	15	13	9.1	0	8.8	55	6.3	0	1.4	55.00
24	snow	46	71	50	50	100	100	98	94	78	54.00
3	lakes and rivers	50	77	55	82	100	97	94	97	93	50.00
26	rain	50	77	73	71	100	97	100	100	96	50.00
11	evaporation	50	71	68	58	91	91	83	49	77	42.00
1	water	88	97	91	97	100	100	98	100	96	12.00

APPENDIX G

CLASS DISTRIBUTION ACROSS CLUSTERS GROUPED BY SIMILAR CONCEPTS-CONNECTED

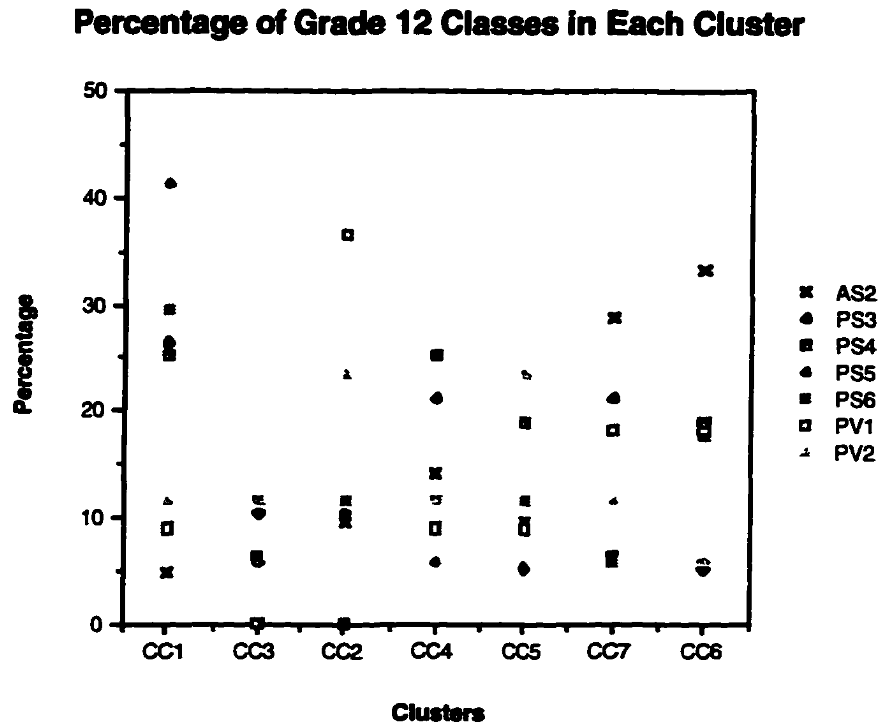

Figure G1. The percentage of each Grade 12 class in each of the seven clusters of similar concepts-connected is shown. Clusters are ordered by complexity.

Unexpectedly high percentages of four twelfth grade classes are represented in cluster 1, and a large percentage of one class have maps in cluster 2. In general, higher percentages of twelfth grade classes are found in clusters of greater complexity. This trend is especially evident in the cluster distribution of the Advanced Physics class, AS2.

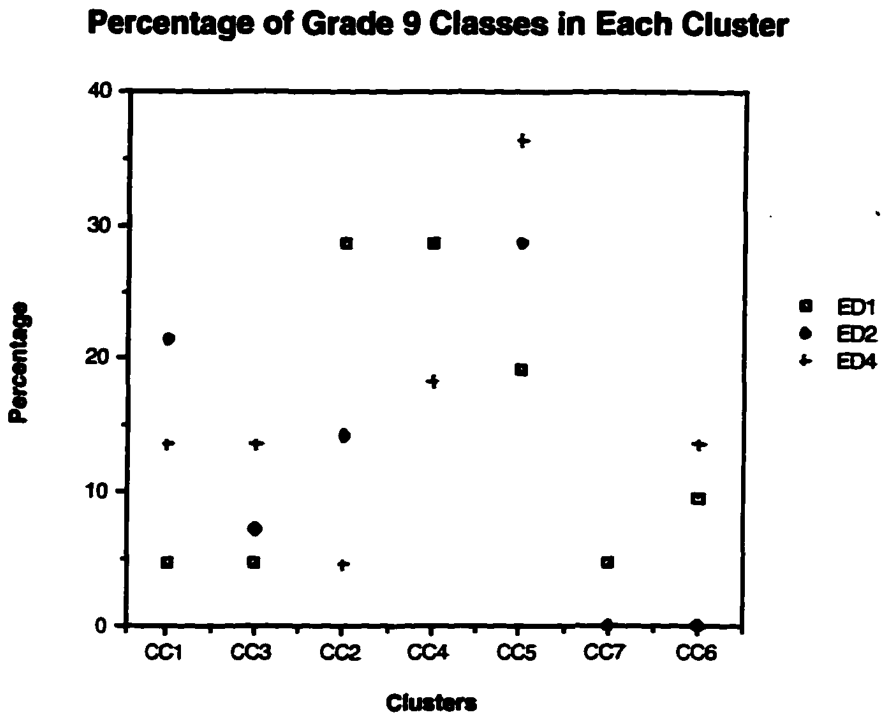

Figure G2. The percentage of each Grade 9 class in each of the seven clusters of similar concepts-connected is shown. Clusters are ordered by complexity.

The highest percentages of each ninth grade class are found in each of the moderately complex clusters of this study. Low percentages of each class are distributed in the most complex clusters.

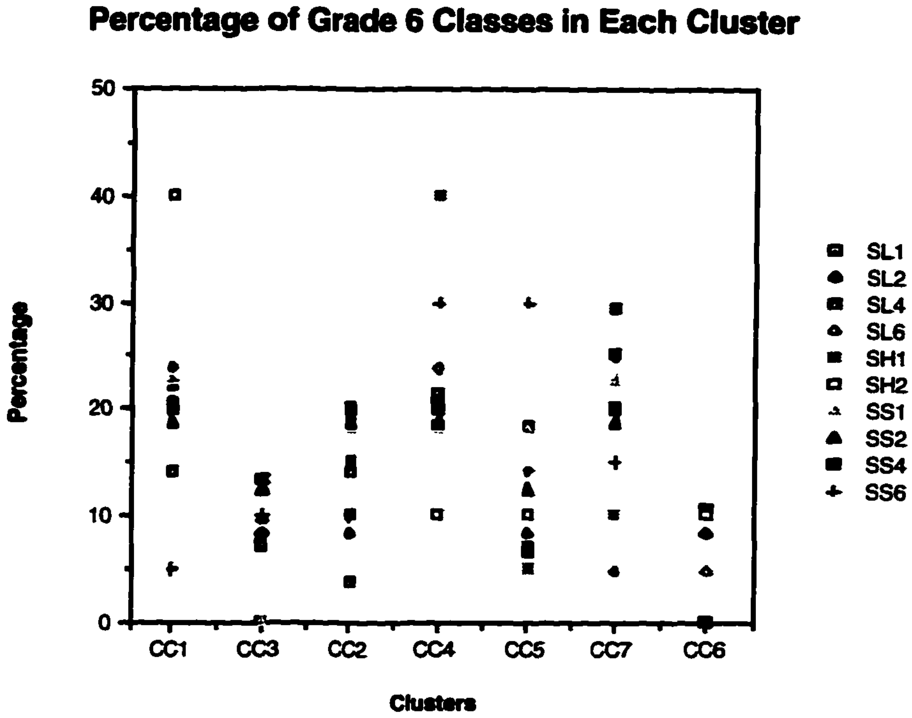

Figure G3. The percentage of each Grade 6 class in each of the seven clusters of similar concepts-connected is shown. Clusters are ordered by complexity.

The highest percentages of each sixth grade class are found in each of the moderately complex clusters of this study. Low percentages of each class are distributed in the most complex clusters. About twenty percent of most sixth grade classes are found in cluster 1, the lowest cluster. About forty percent of one class created maps that sort into cluster 1. Ten percent or less of each class created maps that fall into the most complex cluster 6.

APPENDIX H

DEFINITIONS

accepted relationships or concepts	those that are in agreement with the referent map which may be generated by one or more experts or teachers.
arcs	correspond to links between nodes or concepts; arcs may be directional or non-directional and may be labelled or unlabelled.
clinical interview	a structured interview technique during which the interviewer records student responses and afterwards constructs a concept map based on those responses
cognitive overload	caused by the limited ability to hold information for processing in short-term memory; indicated by an inability to discriminate choices well given longer selection lists
complexity	traditionally a score computed from a formula utilizing the number of correctly linked concepts, the number of levels of branching and the number of correct and significant cross-links indicated; in composite maps, number of cyclic patterns in a concept map, and the number of concepts in cyclic relations.
contiguous core framework	characterizes a group of interconnected concepts
crude grasp of the subject matter	the student concept map has several linked concepts at the first and second levels of hierarchy in common with the experts' concept map; student lacks knowledge of relationships at further levels of detail; student correctly links concepts, indicating recognition of an association between them, but does not correctly specify the link and directionality of the relation.
expert	a recognized professional such as a professor, graduate student, or experienced teacher of the domain; has a depth of understanding of the domain and often relates concepts differently than non-experts

free mapping	process of creating idiosyncratic concept maps using concepts and linking words of student's own choosing
hierarchical	nodes are organized with the broadest, most subsuming at the top of the map and most specific and subordinate at the bottom of the map
links	relationships between nodes or concepts which may be dynamic, descriptive, or elaborative in nature
misconceptions	concepts are incorrectly linked, generally showing evidence of naive beliefs rooted in everyday experience rather than in scientific fact or theory; incorrect links reflecting common beliefs or perceptions of non-experts in the domain
missing knowledge	relations that are omitted from the map
nodes	contain concepts, mathematical equations, or symbols
novices	typically show evidence of misconceptions or are missing knowledge within the domain
other measures	includes other typical assessments of student progress within the discipline such as test scores, class performance, and overall grade in the class
relatedness	is measured by the summation of the horizontal and vertical matrix occurrences for a given concept. Relatedness corresponds to the total number of links both To and From the Concept.
strength	average percentage occurrence for all concept pairs represented in a given composite concept map for a cluster
topology	proximity or nearness will indicate closely related ideas; symmetry will show parallel relationships; geometry of the represented relations

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