Visual Thinking Networking Promotes Problem Solving Achievement for 9th Grade Earth Science Students[1]

Palma J. Longo
University of Massachusetts Dartmouth
North Dartmouth, MA.

O.R. Anderson
Columbia University, Teachers College, New York, N.Y.

and

Paul Wicht
Byram Hills High School
Armonk, N.Y.

[1] The brain graphics and visual thinking networks (VTNs) appearing in this manuscript were created in color. The color component of the VTNs is an essential feature of the findings if reading the manuscript in black/white.

Abstract

An experimental (pre-post control) and interview based-design was used to test the efficacy of a new generation of knowledge representation and metacognitive learning strategies called visual thinking networking (VTN). These new strategies are conceptualized from the current understanding of how one builds a picture of the external world, stores, and recalls this new knowledge from memory. Students constructed network diagrams on paper using black pens or colored pencils to make their drawings, These network diagrams contained words (semantic elements) and figural elements connected by lines and other representations of linkages to represent knowledge relationships. This article addresses one of the main research questions; i.e., to what extent earth science learning was improved by students utilizing VTN strategies compared to controls who used other strategies of learning including writing assignments. A multi-covariate analysis was conducted on the pre-post gain scores of the AGI/NSTA Earth Science Examination (Part 1) from fifty-six 9^{th} grade earth science students. Findings from this analysis significantly established a causal relationship between the improvement of earth science learning and the utilization of visual thinking networks. Earth science learning was improved in the area of problem solving for those students who used VTN strategies (color and black/white). Students who used the VTN strategies (color or black/white) had a significantly higher mean gain score on the problem solving criterion test items than students who used the writing strategy for learning science ($p = .005$). Earth science learning was most improved in the area of problem solving for those students who used color VTNs. Students who used the color VTN strategies for learning science had a significantly higher mean gain score on the problem solving criterion test items than students who used the black/white VTN ($p = .003$) and the control group that used writing strategies ($p < .001$) for learning science. The use of color VTN strategies enhanced problem solving achievement gains for female students. The findings indicated the importance of using color in VTN strategies. The use of color promoted the encoding and reconstruction of earth science knowledge in memory and enhanced the higher order thinking skills of problem solving. A new metacognitive learning theory (ENACT-AC) is proposed as an explanation for these findings.

Introduction

This introduction sets the stage for elaborating the significant findings on problem solving achievement by providing four important aspects that describe and support visual thinking networking as a new knowledge representation and metacognitive learning strategy. First, descriptive characteristics of the VTN strategy are presented. Second the conceptual framework of some previously developed theory driven strategies are critiqued. Since the VTN strategy is derived from the current understanding of how one builds a picture of our external world, stores this new knowledge and recalls it from memory, an overview of the empirical neurocognitive findings is provided so connections can be made as to why the use of the color VTN strategies promoted the highest level of problem solving achievement. Finally, the status of research in problem solving from the context of metacognition, metacognitive learning strategies, visual and earth science learning is described. The introduction concludes with a set of specific research questions that framed this study.

Characteristics of a visual thinking network

Visual thinking networking represents the most recent metacognitive and knowledge representation strategy (KRS) used to enhance student learning (Fisher, Wandersee & Moody, 2000; Longo 2001a, 2001b, 2002). As a new theory driven strategy VTN encourages the learner to integrate multiple ways of thinking that inform concept formation. VTN was being developed at the time Anderson (1991, 1992, 1997) began paving a crucial path in science education, linking the empirical and theoretical findings from neurobiology and neurocognitive science to a constructivist view of learning.

Students use VTNs for organizing their science knowledge by constructing black and white or color network diagrams on paper using semantic and pictorial elements to represent knowledge relationships. Different exemplars are displayed in Appendices 1-5. It is important to note that although Cliburn (1990) used color coding in concept mapping, no study had been previously conducted to test the effectiveness of adding this attribute with respect to student learning and achievement. As a metacognitive learning strategy, VTN "empowers the learner to take care of her/his own learning in a highly meaningful fashion" (Novak, 1998a, p.1). The term "visual thinking" is derived from the work of Rudolf Arnheim (1969). For Arnheim "the perception of shape marks the beginning of concept formation" (p. 27).

Bloom's contextual mapping (1995) represented a critical shift towards enhancing learning away from students constructing meaning solely derived from propositional (semantic) relationship to a strategy that encourages the "emotion-values-asethetics, interpretive frameworks, personal experiences, and metaphors" (p. 169). Visual thinking networking extends the notion of Bloom's "contexts of meaning" by offering a place for learners to incorporate her/his visual metaphors as referents for non-concrete experiences. These metaphors specify meaning and aesthetic quality with the use of color and symbolic visualizations, in addition to incorporating knowledge derived from propositional relationships. VTN, then, is a tool for the learner to represent, organize, and revise her/his meaning-making of science knowledge by chunking and linking conceptual labels with symbolic visualizations of scientific concepts, processes, and experiences into a coherent whole. The planning, organizing, the making of the chunks and the connections are undirected by the teacher and become an aspect that is most crucially idiosyncratic and imaginative.

Theory Driven Strategies

Appendix 6 identifies the knowledge representations strategies (KRS) developed over the past twenty five years in the United States. These KRS differ in many ways, such as the process or the way knowledge is constructed, the product representing the constructed knowledge, and most importantly the theoretical or conceptual framework from which each KRS is derived. The VTN strategy shares some of the characteristic properties of previously established KRS. As in concept mapping, clustering, semantic networking, the concept node in the VTN is the unit of knowledge construction. These nodes are the nouns we use to describe phenomena, the objects and events in our world. Like concept mapping and semantic networking, the concept nodes in VTNs are connected by verbal and or prepositional links that establish relationships between concept nodes. As in semantic networking, VTNs uses directional, bi-directional and cross-links to specify the nature of the relationship between concept nodes and is non hierarchical in organization.

Three of these KRS strategies, concept mapping (Stewart, VanKirk, & Rowell; Novak, 1981), clustering (Rico, 1983; Ambron, 1988), and mind mapping (Buzan, 1979, 1991, 1994) are derived from older neuroscience perspectives. The use of the clustering technique for learning science and the popularized, yet un-researched method of mind mapping are conceptualized from a faulty paradigm. The right/left brain dichotomy in styles of thinking is a view no longer supported by current neurocognitve research (Kosslyn, 1993, 1995; Efron, 1990; Brown & Kosslyn, 1993; Hellige, 1993; Luh & Levy, 1995). Simple dichotomies such as the idea that the left hemisphere is exclusively the locus of analytical and verbal representations, and the right is holistic and spatial are no longer tenable. Neither hemisphere is said to be the seat of mental imagery (Brown & Kosslyn, 1993). Rather a broader view supports “interhemispheric cooperation” (Luh & Levy, 1995, p. 1243).

The neurophysiological rationale for concept mapping (MacGinn, 1987) exposes another conceptual limitation. MacGinn's framework for this level of analysis is limited to the cellular level and makes no link to the level of the learners' cognitive system.

Perspectives from current neurocognitive science conceptually ground VTN as a new heuristic for learning science

With the advent of new technologies to collect data about cognitive processes and the increasing ability to link these processes to neural events our understanding about attention, perception, and memory has become more precise and elaborate (Posner &

Raichle, 1994). Old findings are giving way to new ones and thus the ground from which these knowledge representation strategies are derived, shifts. Neurocognitive science is a new and highly interdisciplinary field of study that bridges the concepts and methods from three main disciplines, neuroscience, experimental psychology, and computer science (Gazzaniga, 1995, 2000; Kosslyn & Andersen, 1992).

Although a detailed elaboration of the empirical and theoretical findings from neurobiology and neurocognitive science are presented in the larger comprehensive study (Longo, 2001a), a succinct overview of five new neurocognitive findings is provided for two reasons. First, to establish the conceptual framework that grounds and drives the VTN strategy. Second, to make connections between this conceptual framework, the significant findings in problem solving achievement, and the ENACT-AC model, a new metacognitive learning theory that offers an explanation as to why the use of color VTN strategies promoted the highest level of problem solving achievement.

Neurcognitive Finding 1: *Knowledge is distributed anatomically to separate regions of our brain.*

When we look at a landscape as depicted in Figure 1, our early visual processing system categorizes the visual world into constructs of color, shape, location, and motion (Zeki, 1988, 1991, 1990, 1993; Martin, Haxby, Laonde, Wiggs & Ungerleider, 1995; Ungerleider, 1995).

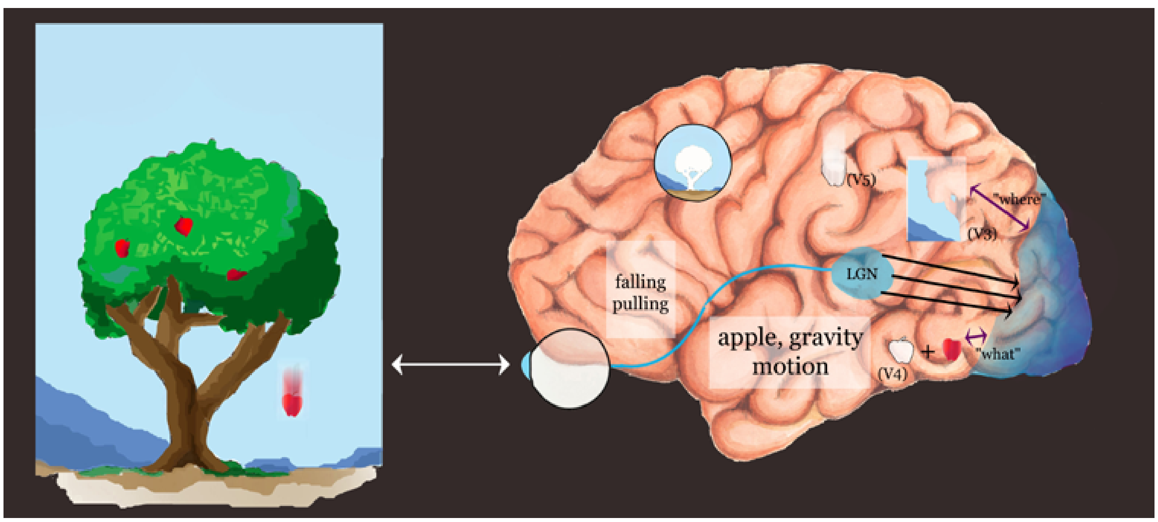

Figure 1. *Distributed knowledge: a new conceptual framework for concepts in the brain.* Here we see an apple falling from a tree. The visual information of the apple falling from the tree travels from the optic nerve to the lateral geniculate nucleus (LGN) in fundamentally a parallel pathway. This structure acts as a relay station so that visual signals are sent to the primary visual cortex (blue). The early visual processing system functions to build a picture of our external world into two pathways that are more serially organized. The ventral, "what" pathway categorizes the external world into attributes of color and form with color (V4), while the dorsal, "where", pathway categorizes the

external world into attributes of motion (V5) and spatial relations (V3). The segregated states of these attributes are maintained in the frontal cortex of the brain. The nouns like apple, gravity, and motion and the verbs such as falling and pulling that we use to describe these objects and events in our external world are also located in different regions of the brain (Longo, 2001a, p. 30).

The new role of the cerebral cortex as a categorizer of knowledge gives rise to the notion of "seeing as understanding" (Zeki, 1993, p. 3). Damasio (1989, 1992) argues for a broader definition of a concept in the brain as not just being a word, a definition, or a picture, but rather a collection of neural ensembles that have a high probability of firing simultaneously.

Neurocognitive Finding 2: *The old conceptual framework on the strict hierarchical organization of the visual cortex collapses. The visual cortex is viewed as a distributed network, where processing is concurrent and simultaneous.*

For a long time, it was thought that the nervous systems builds an image of the external world by analyzing it's components and then assembling the analyzed components at successive stages of the visual pathways by simple addition. This notion of analysis from a strict hierarchical organization and processing is being replaced by a conceptual understanding in which the cerebral cortex is viewed as a distributed network where multiple or concurrent processing of visual information is distributed over several cortical areas including the pre-frontal lobes through feedforward and feedback neural linkages (Felleman, Van Essen, 1992; Goldman-Rakic, 1993; Friedman *et al* 1994; Martin *et al*, 1995; Ungerleider, 1995). These elaborate feedforward and feedback connections promote a dynamic interaction among the various processing centers of the brain. (Young 1992, 1993, 1994; Felleman & Van Essen, 1991; Rockland & Van Hoesen, 1994; Salin & Bullier, 1995). Perception and cognition are viewed as "continuous and coextensive processes" (Squire & Kandel, 1993, p. 147). The highly interconnected neural streams that carry this distributed knowledge from the visual cortex are maintained through one of the most important parts of the brain, the frontal cortex (Figure 2).

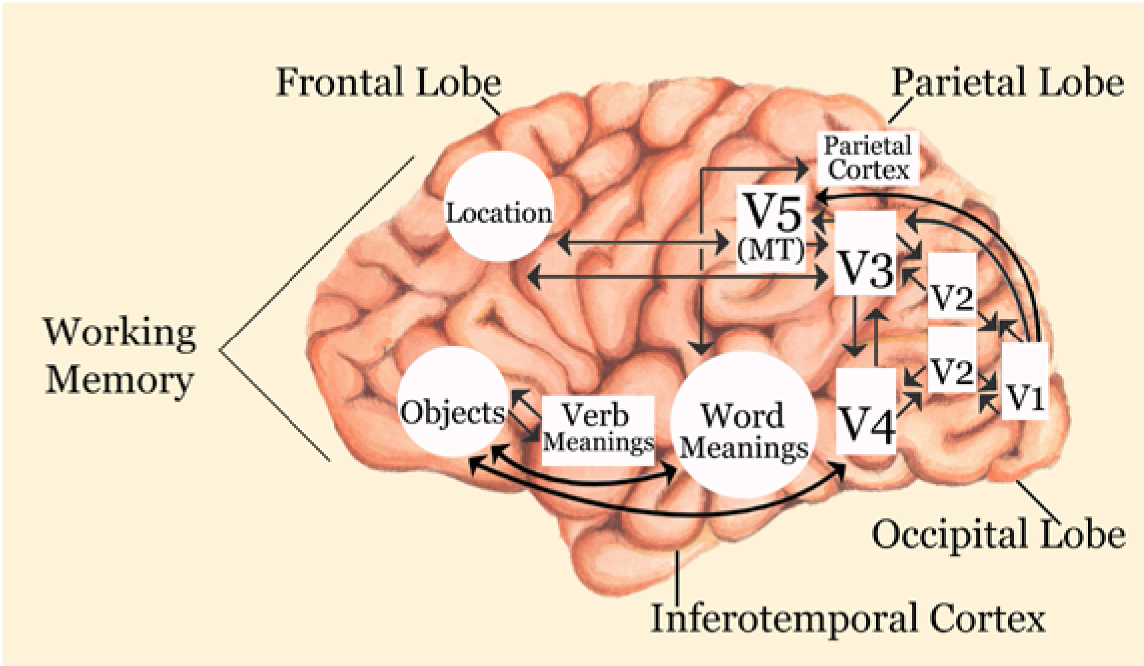

Figure 2. *The distributed knowledge is highly interconnected.* Projections from the primary visual cortex (V1) in the occipital lobe establish a richness of feedforward and feedback neural connectivity to V2, V4 (color), V3 (location), and V5 (motion). These connections continue to and from the frontal lobe where the functional processes of planning, organizing, and working memory occur. The anatomical area for our word meanings and verb meanings also maintain cortical connections to and from the working memory area for objects in our physical world (Longo, 2001a, p. 32).

Neurocognitive Finding 3: *The early visual categorizations have a functional role in cognitive processing.*

Although the exact mechanisms have not been clearly established, the early visual constructs of color, form, spatial relations, and motion that were established by a perceiver sensing an object or event are implicated in the brain's attentional and memory systems (Corbetta *et al*., 1991; Corbetta, Shulman, Miezin, & Petersen, 1995; Hanna & Remington, 1996; Damasio *et al*, 1993; Farah, 1989; Kosslyn, Thompson, Kim & Alpert, 1995; Kosslyn, *et al*., 1993; Le Bhihan *et al*., 1993). The mechanisms of attention, perception, and memory mediate the cortical functions of language and reasoning. The frontal cortex functions in the cognitive processes of planning, organizing, and working memory (Courtney, Ungerleider, Keil & Haxby, 1996; Friedman & Goldman-Rakic, 1994; Smith, Joindes, & Koeoppe, 1996; Wilson, Schalaidhe & Goldman-Rakie, 1993). Working memory is the temporary store of memory information that allows for the manipulation of that information and is fundamental for language comprehension, reasoning, and decision making (Goldman-Rakic, 1992). Novak described working memory as the "most critical memory system for incorporating knowledge into long-term memory" (Novak, 1995, p.232). According to Novak, it is crucial that metacognitive learning tools facilitate working memory capacity. Glynn and Duit's (1995) model of a student's cognitive architecture for learning science place working memory as a central role in learning science concepts within a metacognition framework.

Directing attention to color, motion, or form during the performance of a task activates many of the same cortical areas that were involved in the passively receiving information of the same type (Corbetta *et al.*, 1991; Corbetta, Shulman, Miezin, & Petersen, 1995). The anterior cingulate has been hypothesized as an executive attention system (Posner and Raichle, 1994). This system helps to ensure that the processing in other brain regions is most efficient. The empirical work of Hanna and Remington (1996) found that color and form can be represented separately and accessed independently in long term memory.

Neurcognitive Finding 4: *Formation of visual images from both right and left brain hemispheres activate the early visual cortical networks.*

Empirical evidence indicate that when visual images are generated the early visual cortices become activated (Damasio *et al.*, 1993; Farah, 1989; Kosslyn, Thompson, Kim, & Alpert, 1995; Kosslyn, et al., 1993a ; Le Bihan *et al.*, 1993). Visual mental images are generated by both right and left hemispheres. Visual images are not solely semantic or language-like (propositional) representations. Thinking visually relies on depictive representations that are topographically organized in regions of the primary visual cortex (Farah, 1994; Kosslyn, 1995; Albright, 1995; Tootel, 1982). Visual mental images are fundamentally different from verbal thoughts but the two can be interconverted through neural linkages connecting processing centers mediating each of these representations.

Neurocognitive Finding 5: *The brain stores and retrieves this categorized knowledge from anatomically segregated areas rather than from one integrated form.*

The most salient aspect emerging from this finding with respect to how an individual retrieves information from memory is that knowledge retrieval relies on the active phase of reconstruction of the distributed knowledge (Anderson, 1991, 1992, 1997; Anderson & Demetrius 1993; Bradsford, Sherwood, Hasselbring, Kinzer & Williams, 1990; Damasio & Damasio 1994a). When an individual seeks to recall an experience from memory, all those multiple constructs of color, shape, form, motion, even the cortices where the nouns and verbs are located that were used to describe the original events and objects are re-activated just as there were established during the perceiving of an event or object. Thus all these neural ensembles, the original patterns of activity, fire simultaneously and experience is recalled as a whole unitary event, and not as separate categorizations.

In essence this notion of the reconstruction of memory establishes and reaffirms Anderson’s position of a neurocognitive basis for constructivism (1991, 1992, 1997, 1999). Thus from this new perspective on constructivism, distributed knowledge gives rise to a new understanding of how our experiences are semantically and iconically represented in the brain. Visual thinking networking strategies encourages the learner to integrate multiple ways of thinking that inform concept formation by utilizing the same categorizational attributes of form, color, and motion, and spatial relationships that our brain utilizes when perceiving events in the physical world.

Problem Solving Research in the context of Metacognition, Metacognitive Learning Strategies, Visual and Earth Science Learning

Davidson and Sternberg (1998) describe a process that explains how metacognition helps problem solving. This process involves four main steps each having derivative elements. These steps involve: (1) encoding, (2) the creation of a mental representation that depict relationships among the givens, (3) effective planning to reach the goal, and (4) the ability to transfer this skill to a novel problem. These steps described in problem solving represent a parallel sequence to the building of a visual thinking network.

When a student constructs a visual thinking network they encode the science knowledge by identifying salient features, in the form of words, color, and or shapes. A two dimensional representation of semantic and figural elements is constructed on paper. We are not arguing here that the network is a replica of the learner's internal cognitive map, but rather an operational expression of an inner representational state. Relationships are then created by the nature of the constructed verbal links and cross links. It is unknown at this time whether the planning of the network structure happens continually throughout the process of reflection as changes in the network are made or whether the learner has a specific temporal and procedural order of connecting the elements at the beginning of network building.

The construction of a visual thinking network can be viewed as a problem space to solve with a goal of building a meaningful structural knowledge base that shows relationships between concepts, principles, and theories. Overtime the novice learner should then have the capacity to transfer this problem solving skill to new situations. According to Novak (1998), since "metacognitive strategies are strategies that empower the learner to take charge of her/his own learning in a highly meaningful fashion… the learner who has knowledge organized into large, integrated conceptual frameworks can assimilate more related knowledge in less time and with greater potential for transfer and application" (p. 1).

The research on problem solving in science in the context of metacognitive learning strategies is very limited. Ault's (1994) thorough analysis of earth science problem solving research identifies only one study that examined the effectiveness of the concept mapping strategy and Vee mapping with respect to changes in problem-solving performance (Novak, Gowin, and Johansen, 1983). The underlying assumption of this study was that "meaningfully learning leads students to organize knowledge hierarchically with consequent improvement in their ability to use this knowledge" (p. 636). In this study the problem solving task was described as the "Winebottle Test" where eighth grade students had to solve the problem as to why a cork would pop out of an empty wine bottle that was placed in sunlight after a night in a cold refrigerator. The control group was asked to write a paragraph that answered the question, while the experimental group was first asked to construct a concept map that described the problem then to rewrite the concept map in paragraph form. Analysis of experimental and control groups performance was based upon scoring valid semantic relationships derived from a written paragraph that answered the problem question. The experimental group constructed twice as many valid semantic relationships than the control group. The conclusion cited from this study suggested that “concept mapping and Vee mapping are helpful” (p. 643) in the context of changes in the learners’ science knowledge base and in problem solving.

Like other science disciplines, the structure of earth science knowledge is embodied with rich visual contexts that emerge from conceptual models and the natural events and objects in our physical world. Ault presents compelling arguments that the capacity to visualize and visual reasoning are critical skills for earth science problem solving. Utilizing examples from earth science phenomenon, Ault demonstrates that "nearly all earth science instruction can tap a wealth of everyday experiences and imagery" (p.281). The relationship of these visual skills to learning and achievement have been documented in the earth (Keig & Rubba 1993), biological (Macnab, 1991) and chemical sciences (Baker & Talley 1972, 1974; Hill & Obenauf 1979; Gabel & Bunce 1994).

The Research Questions

The section of the experimental design that sought to find out if earth science learning was improved by students choosing and utilizing VTN strategies was driven by six specific research questions with respect to earth science knowledge achievement and cognitive level of earth science knowledge achievement.

<u>Earth Science Knowledge Achievement</u>

1. Are there differences in the pre-post test achievement gain scores on an earth science exam between groups that utilized VTN strategies for science learning and those who utilized a writing strategy for learning science?

2. Are there differences in the pre-post achievement gain scores on an earth science exam between groups who utilized different VTN strategies for learning science?

3. Are there differences in the pre-post achievement gain scores on an earth science exam between groups who used different VTN strategies for learning science and a group who utilized a writing strategy for learning science?

Cognitive Level of Earth Science Knowledge Achievement

4. Are there differences in the pre-post achievement gain scores on the four Gagnean cognitive levels (fact, concept, rule/principle, problem solving) of an earth science exam between groups who utilized VTN strategies for learning science and those who utilized the writing strategy for learning science?

5. Are there differences in the pre-post achievement gain scores on the four Gagnean cognitive levels (fact, concept, rule/principle, problem solving) of an earth science exam between groups who utilized different VTN strategies for learning science.

6. Are there differences in the pre-post achievement gain scores on the four Gagnean cognitive levels (fact, concept, rule/principle, and problem solving cognitive level) of an earth science exam between groups who utilized different VTN strategies for learning science and those who used a writing strategy for learning science?

Methodology

Population and setting

A carefully controlled long-term, ten-month study was conducted in natural classroom settings with fifty six 9th grade earth science students (13-15 years of age). Thirty-four students were females (n = 34) and twenty-two (n = 22) were males. The site was a small suburban high school outside of NYC. Students were randomized into three classes with the same earth science instructor according to gender, age, and achievement. One class was the control group (writing strategy, n = 21) and two classes were the experimental (VTN strategy, n = 20, n = 18). During the entire academic year, each of the three classes received the same earth science instruction (lecture and laboratory) from one teacher. One of the main research questions was: To what extent is earth science learning improved when students use VTN strategies compared to controls who use a placebo consisting of a writing project? The outcome or dependent variable in this experimental design was achievement, with two levels: earth science knowledge and Gagnean cognitive levels of achievement as summarized in Table 2. Abstract reasoning aptitude was the independent variable with gender as the mediating variable.

Utilization of VTN and Writing Strategies for Learning Science

VTNs were used as a metacognitive learning tool for representing earth science knowledge acquired throughout the academic year. At the conclusion of three major units of study (earth in space, the atmosphere, and solid earth/earth's history), both the experimental and control groups were given the same set of earth science concepts that characterized each unit (Appendix 7). The VTN or experimental group had the choice of constructing knowledge that represented four different levels:

- Level 1: Networks of conceptual labels in black/white (Appendix 5).
- Level 2: Networks of conceptual labels in color (Appendix 4).
- Level 3: Networks of conceptual levels with black/white symbolic or pictorial images (Appendix 3).
- Level 4: Networks of conceptual labels with color symbolic or pictorial images (Appendix 1 & 2).

During the course of treatment these students could change to any other level(s) of representing knowledge. Data was tabulated to determine the most frequently used VTN level. The experimental group was given no instruction in how to think visually with respect to earth science objects or events. They were however, given guidelines as how to construct a VTN (Appendix 7). The writing strategy or control group was given instructions (Appendix 8) on how to use a variety of writing strategies, such as fictional writing or prose to express their understanding of the same set of earth science concepts. During the twenty-two weeks that students developed their networks or writing strategies they participated in scheduled "help sessions" that would follow the progress and answer questions about the newly developed strategies. Outside of these 'help sessions' students worked on these networks and writing strategies out of classroom instruction time. At the conclusion of three major earth science curriculum units, each student submitted either a final network or writing strategy for their portfolio assessment. As much as possible, the time on task for the VTN treatment group and the control group was equivalent.

The AGI/NSTA Earth Science Examination Instrument

The American Geological Institute/National Science Teachers Association Earth Science Examination; Version 1988A and Version 1988B (Callister, Higham, Mayer, Sproull, & Stroud 1988) was used to measure two dependent variables: the subjects' domain specific knowledge of earth and space science and the Gagnean cognitive levels of the earth science knowledge. This instrument was developed by the National Science Teachers Association with the assistance of the American Geological Institute and was recognized to be the most reliable instrument available for assessing students' knowledge of the earth and space sciences from grades 9-12 (Krockover, 1990). The Kuder-Richardson measure of reliability for Form A is.89, and for Form B is .86 (Stewart, 1988). As stated in the published documentation on the objectives of the test:

> The test was specifically designed to include questions that stress more than just facts and concepts. Questions assess students' problem solving abilities, understanding of the relationship between science and technology, and understanding of the nature of science. More than half of the questions require an understanding of and an ability to apply concepts, many by asking for interpretations of maps, diagrams, and tables. (Callister & Mayer, 1988, p. 34).

The Gagnean levels assessed by the test are presented in Table 2 . Data on the reliability of this categorization can be found in Barba (1990). Part I of the AGI/NSTA Earth Science Exam (Form A) was administered to both the experimental and control groups early in the beginning of the academic year as the pre-test measure. For the post-test measure Part I of the AGI/NSTA Earth Science Exam (Form B) was administered to both groups nine months after the pre-test.

Table 2

Percentage of Gagnean Cognitive Levels in Part 1 AGI/NSTA Earth Science Exam

Gagnean Cognitive Level	Percentage
Fact Level	27 %
Concept Level	37 %
Rule/Principle Level	10 %
Problem Solving Level	27 %

The Differential Aptitude Instrument

Spatial visualization and abstract reasoning were independent variables in the design and were measured by the Space Relations and Abstract Reasoning portion of The Differential Aptitude Tests (Bennett, Seashore, & Wesman 1975).

The abstract reasoning section consists of items having no words and requiring an understanding of the rule governing a series of abstract designs and identifying, which one comes next. It measures reasoning skill and careful attention to detail. It measures the ability to understand an idea that are not presented in words or numbers; to see relationships among things, such as object patterns, diagrams, or designs. Reliability measure for the internal consistency of the test was measured by using split-half correlation, Spearman-Brown. The reliability results for 9th grade boys, Form S, r_{ii} = .94, for 9th grade girds, Form S, r_{ii} = .95, (Bennett, Seashore, & Wesman, 1974, p. 63-64).

The space relations section consists of patterns that can be folded into figures. The subject is shown a picture of the object, which is flat and unfolded, and must identify which figure among the choices, can be made from the pattern. It also requires paying attention to details such as the location of the shading and dark dots in the figures. This test is a measure of the ability to think in three dimensions, to picture mentally the shape, size, and position of objects when shown only a picture or pattern. The split-half, Spearman-Brown reliability coefficients are as follows: for 9th grade boys, Form S, r_{ii} = .91, and Form T,r_{ii} = .92; for 9th grade girls, Form S, r_{ii} = .91, and Form T, r_{ii} = .90 (Bennett, Seashore, & Wesman, 1974, p. 63-64).

Pre-Experimental Equivalence

Early in the academic year, four pre-tests were administered to determine the extent to which the groups (experimental, control, and gender) were equal with respect to earth science knowledge, cognitive level of earth science knowledge, abstract reasoning and spatial relations aptitude. These tests were Form A, Part I of the AGI/NSTA Earth Science Exam (Calister, Highmam, Mayer, Sproull, & Stroud 1988) and the Abstract Reasoning and Spatial Relations Test (Bennett, Seashore, & Wesman 1975).

<u>Earth Science Knowledge Equivalence</u>

There was no statistically significant difference between the experimental and control groups at the pre-test level with respect to earth science knowledge [t = .240 (df = 54), p = .811]. Male and female groups however were not equal at the pre-test level with respect to earth science knowledge. Males scored significantly higher than females on the earth science knowledge criterion test items [t = -2.756 (df = 54), p = .008] Gender statistics for the this t-test indicated a mean value of 29.739 for males (n = 23), and for females, 25.000 (n = 33). This finding was expected since it supported other research documenting the gender gap in science achievement (Kahle & Meece, 1994; Beller & Gafni 1996; Parker, Rennie, & Fraser, 1996).

<u>Cognitive Level of Earth Science Knowledge Equivalence</u>

The t-test on the Gagnean cognitive levels of achievement indicated that both the experimental and control groups were equal with respect to all four cognitive levels: fact [t = 1.396 (df = 54), p = .169], concept [t = 1.452 (df = 54), p = .653], rule/principle [t = -.830 (df = 54), p = .410], and problem solving [t = -.473 (df = 54), p = .620]. Since males had a significantly higher mean criterion test scores of earth science knowledge than females, it was important then to establish which cognitive level(s) of earth science knowledge reflected this level of significance. Male and female groups were equal on two of the four Gagnean cognitive levels of earth science knowledge: the fact [t = -1.943 (df = 5r4), p = .057] and rule/principle Gagnean cognitive level [t = -1.017. (df = 54), p = .41]. Males performed significantly better than females on the concept [t = -2.025 (df = 54), p = .048) and the problem solving (p = .015) cognitive levels.

<u>Abstract Reasoning Aptitude Equivalence</u>

Although the t-test on abstract reasoning aptitude between the experimental and control group at pre-test level was not significant [t = 1.562 (df = 54), p = .124], the standard error of the mean indicated a two fold difference. Therefore as a safety factor during statistical analysis, the abstract reasoning aptitude was used as a covariate in allsucceeding analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) tests. The t-test on abstract reasoning aptitude by gender indicated no significance difference between gender groups [t = .965 (df = 54), p =.339].

Spatial Relations Aptitude Equivalence

The t-test on spatial relations aptitude indicated no significant differences between either the experimental and control group [t = -1.544 (df = 54), p = .128] or gender groups [t = -.755 (df =54), p = .453].

Results

Two major statistical tests were performed at an alpha level of .05 The analysis of covariance was conducted on the pre-post earth science knowledge achievement gain scores between the experimental and control groups. A multi-covariate analysis was performed on the pre-post Gagnean cognitive achievement levels between the experimental and control groups. The results are reported with respect to each specific research questions (RQ).

Earth Science Knowledge Level of Achievement

RQ 1: The main effect, as determined by an analysis of covariance, indicated no statistically significant differences in the pre-post achievement gain scores on earth science criterion test items between groups who utilized VTN strategies for learning science and those who utilized a writing strategy for learning science [F = 3.151 (df = 1,) p > .05].

RQ 2: Students who used the color VTN strategies for learning science had a significantly higher pre-post mean achievement gain on the earth science knowledge criterion test items than those who used the black/white VTN strategies for learning science [F = 5.804 (df =1), p = .022].

RQ 3: A significant group effect was found when comparing the pre-post mean achievement gain scores between groups who used different strategies for learning science [F = 5.238, (df = 2), p = .009]. Table 3 provides the descriptive statistics used in the analysis of covariance. Pairwise comparisons were used to determine the source of effect. Students who used the color VTN strategies had a significantly higher pre-post mean gain score on the earth science knowledge criterion test items than those who used the writing strategies [Mean Difference = 4.276, Std. Error = 1.843, p = .014] (Figure 4). No significant gender differences were found in earth science knowledge achievement between these three groups [F = 1.419 (df = 1), p = .239].

Table 3

Descriptive Statistics for Students using Different Strategies for Learning Science

Group	Gender	Mean	Std. Deviation	N
Color VTN	female	13.7500	4.5534	16
	male	18.7500	3.2842	8
	Total	15.4167	4.7541	24
B/W VTN	female	11.6667	2.3094	3
	male	11.8750	4.7340	8
	Total	11.8182	4.0943	11
Writing	female	11.5333	4.6270	15
	male	10.8333	6.3061	6
	Total	11.3333	5.0033	21
Total	female	12.5882	4.4797	32
	male	14.0909	5.8057	24
	Total	13.1786	5.0456	56

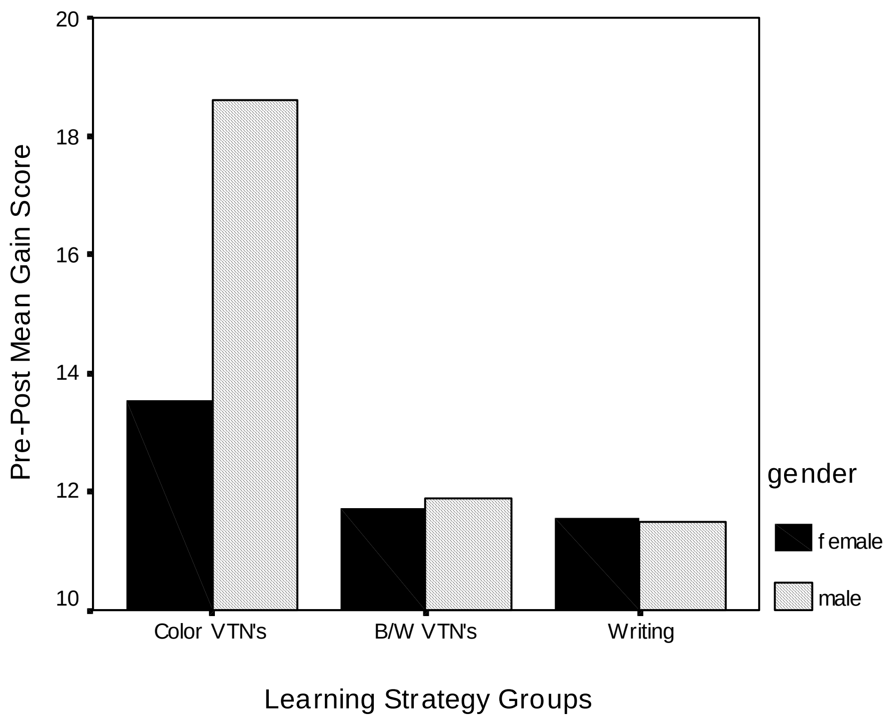

Figure 4. Pre-post mean achievement gain on Part I of the AGI/NSTA Earth Science Exam between students who utilized different strategies for learning science.

Cognitive Level of Earth Science Knowledge Achievement
Since significant differences were found in the earth science knowledge level of achievement between groups who utilized different strategies for learning science, the multi-covariate analysis of the Gagenan cognitive levels was used to determine at what level(s) (fact, concept, principle-rule, or problem solving) this significance occurred

RQ 4: A multi-covariate analysis for achievement with respect to the four cognitive levels indicated a significant difference between the experimental and control group only at the problem solving level [F = 8.470 (df = 1), p = .005]. No significant differences were found between the experimental and control group on the fact [F = 1.113 (df = 1, 56), p > .05], concept [F = .322 (df = 1), p > .05], and rule/principle [F = 1.554 (df = 1) p > ,05].

RQ 5: Students who used the color VTNs scored significantly higher on the problem solving cognitive level of achievement than those who used the black/white VTN strategies for learning science [F = 17.532 (df = 1), p < .001]. No significant differences were found between the color and black/white VTN groups on the fact [F = .814 (df = 1, 35), p > .05], concept [F = .273, (df = 1, 250, p > .05], and rule/principle cognitive levels [F = .575 (df = 1), p > .05]. Males scored significantly higher than females on the problem solving cognitive level of achievement [F = 9.480 (df = 1), p = .004] as shown graphically (Figure 5).

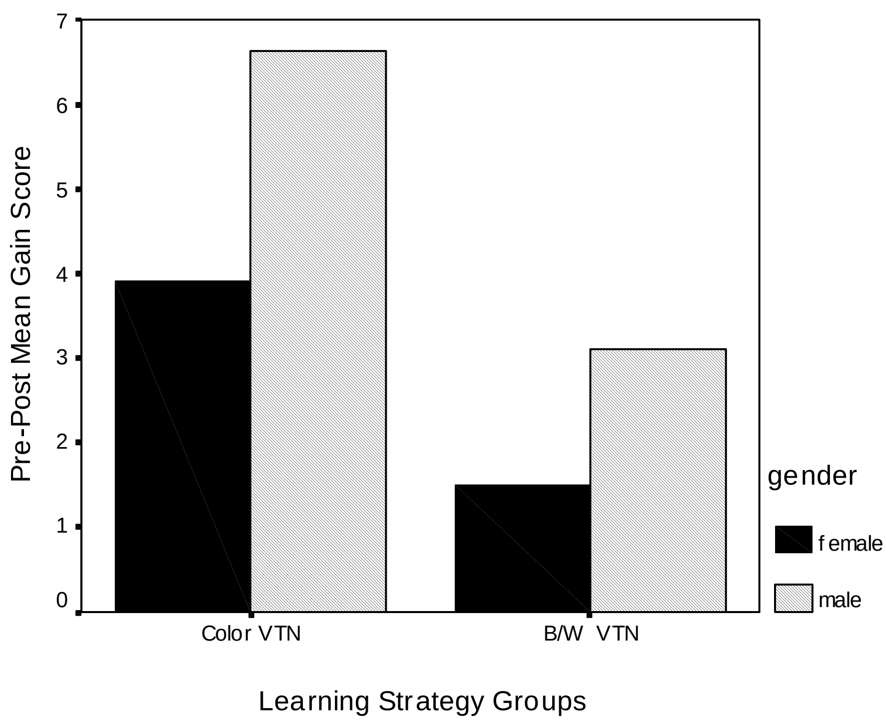

Figure 5. Pre-post mean problem solving achievement gain on Part 1 of the AGI/NSTA National Earth Science Exam between groups who used the color and black/white VTN strategies for learning science.

RQ 6: A very significant group effect was found [F = 12.067 (df = 1), p < .001] when comparing students who used different strategies for learning science at the problem solving achievement level. No significant effect was found at the fact [F = .867 (df = 2), p = .425], concept [F = .462 (df = 2), p = .633], or rule/principle cognitive level [F = 1.517 (df = 2), p = .230]. Appendix 9 summarizes the descriptive statistics for this MANCOVA. Pairwise comparisons were performed to determine between which groups there was a significant effect. Students who used the color VTN strategies had a significantly higher mean gain score on the problem solving criterion test items than students who used the black/white VTN strategies [Mean Difference = 3.048, Std. error = .875, p = .003] and the writing strategy for learning science [Mean Difference = 3.298, Std. error = .732, p < .001]. Males scored significantly higher than females on the problem solving achievement level [F = 4.602 (df = 1), p = .037]. A graphic plot displays these findings (Figure 6).

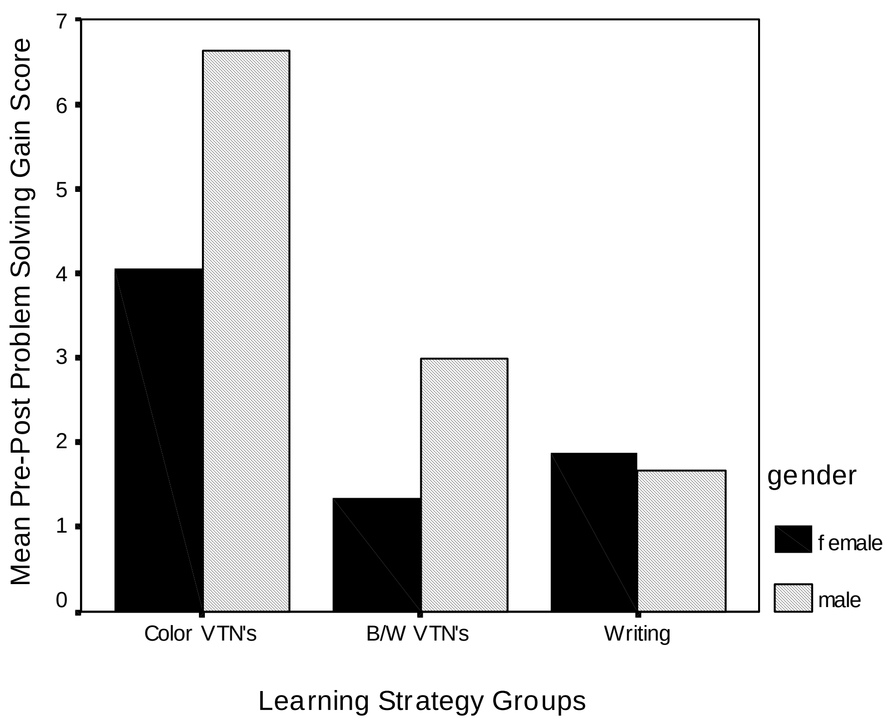

Figure 6. Pre-post mean problem solving achievement gain on Part 1 of the AGI/NSTA Earth Science Exam between groups who used different strategies for learning science.

Post-hoc Analysis of Problem Solving Achievement and Aptitude

A series of post-hoc ANCOVA's were performed to compare differences in problem solving achievement with respect to abstract reasoning and spatial relations aptitude.

Abstract Reasoning Aptitude. A significant group effect was found between students with high abstract reasoning aptitude who used different strategies for learning science [F = 8.264 (df = 2), p = .002]. Table 4 summarizes the descriptive statistics. Pairwise comparsions indicated that students with high abstract reasoning aptitude who used the color VTN strategies had a significantly higher mean gain score on the problem solving criterion test items than the high abstract reasoning students who used the black/white VTN [Mean Difference = 3.763, Std. Error = 1.358, p = .010 and the writing strategy for learning science [Mean Difference = 3.311, Std. Error = .919, p = .001]. No significant differences were found between students with low abstract reasoning aptitude who used different strategies for learning science [F = 1.126 (df = 2), p = .591]. No significant differences were found between students with middle abstract reasoning aptitude who used different strategies for learning science [F = .488 (df = 2), p = .628].

Table 4

Descriptive Statistics of Mean Problem Solving Achievement Gain for High Abstract Reasoning Aptitude Students who used Different Strategies for Learning Science

Group	**Gender**	**Mean**	**Std. Deviation**	**N**
Color VTN	female	4.7273	1.9540	11
	male	6.6000	1.1402	5
	Total	5.3125	1.9225	16
B/W VTN	female	1.0000	.	1
	male	2.3333	3.0551	3
	Total	2.0000	2.5820	4
Writing	female	1.6250	3.3780	8
	male	2.0000	2.0000	3
	Total	1.7273	2.9695	11
Total	female	3.3000	2.9753	20
	male	4.1810	2.9264	11
	Total	3.6129	2.9403	31

Spatial Relations Aptitude. A significant group effect was found between students with low spatial relations aptitude who used different strategies for learning science [F = 12.800 (df = 2), p <.001). Table 5 summarizes the descriptive statistics. Pairwise comparison indicated that students with low spatial relations aptitude who used color VTN strategies had a significantly higher mean gain score on the problem solving criterion test items than students with low spatial relations aptitude who used the black/white VTN strategy [Mean Difference = 3.076, Std. Error = 1.269, p = .024] and the writing strategy [Mean Difference = 3.748, Std. Error = 1.041, p = .002] for learning science.

Table 5

Descriptive Statistics of Mean Problem Solving Achievement Gain for Low Spatial Relation Aptitude Students who used Different Strategies for Learning Science

Group	**Gender**	**Mean**	**Std. Deviation**	**N**
Color VTN	female	4.0000	2.1909	11
	male	6.7500	.5000	4
	Total	4.7333	2.3509	15
B/W VTN	female	1.3333	1.5275	3
	male	2.0000	4.2426	2
	Total	1.6000	2.4083	5
Writing	female	1.5000	1.2910	4
	male	1.0000	3.4641	4
	Total	1.2500	2.4249	8
Total	female	3.0000	2.2492	18
	male	3.5000	3.7491	10
	Total	3.1786	2.8160	28

Gender Effect on Cognitive Level of Problem Solving Achievement

At the pre-test level a significant gender effect was found on two of the four Gagnean cognitive levels. Males performed significantly better than females on the concept (p = .048) and the problem solving (p = .015) cognitive levels. At the pre-post gain level, while males still out performed females on the problem solving cognitive level [F = 4.602 (df =1), p = .037], no significant differences where found at the concept level [F = .462 (df = 2), p = .633]. Closer examination of the mean pre-post achievement gain at the problem solving level (Appendix 9) indicated that females who used the color VTN strategies achieved a higher mean problem solving gain score (Mean = 4.000, SD = 2.0331) than the males who used the black/white VTN strategy (Mean = 3.000, SD = 1.9272) and the males who used the writing strategy (Mean = 1.667, SD = 2.9439). Is this significant? That is, did the utilization of the color VTN strategies for those females enhance their problem solving achievement? An ANCOVA was performed comparing the mean pre-post problem solving achievement of females who used the color VTN strategy to the collective males high abstract reasoning aptitude subjects from the black/white VTN and the writing strategy group. Females students had a significantly higher mean gain score on the problem solving criterion test items than males students who used the black/white VTN and the writing strategy for learning science [F = 6.738 (df = 1), p = .021].

Male students who used the color VTN strategies had a significantly higher mean gain score on the problem solving criterion test items than male students who used the black/white VTN [Mean Difference = 3.546, Std. Error = .987, p = .006] and the writing strategy for learning science [Mean Difference = 4.483, Std. Error = 1.1137, p = .001]. Female students who used the color VTN strategies had a significantly higher mean gain score on the problem solving criterion test items than female students who utilized the writing strategy for learning science [F = 5.561, (df = 1), p = .025].

Discussion and Implications for Instructional Practices

Five major positive findings emerged from this phase of the experimental design with respect to problem solving achievement:

- Earth science learning was improved in the area of problem solving achievement for those students who used VTN strategies (color and black/white).
- Earth science learning was most improved in the area of problem solving achievement for those students who used color VTN strategy.
- Earth science learning was most improved in the area of problem solving achievement for students with high abstract reasoning aptitude who used the color VTN strategy.
- Earth science learning was most improved in the area of problem solving achievement for students with low spatial relations aptitude who used the color VTN strategy.
- Color VTN strategies enhanced problem solving achievement gains for female students.

Identification of a Causal Relationship and Classroom Implications

These findings significantly establish a causal relationship between the utilization of visual thinking networking strategies and problem solving achievement in earth science. Although significance was found in terms of problem solving achievement, what does this mean in terms of classroom practice? Table 6 summarizes the percentage gain in problem solving achievement in terms of total possible score on the problem solving area of the AGI/NSTA Earth Science Exam. The experimental group had a twenty-six percentage (26%) achievement gain while the control group had a twelve percentage 12% gain. This doubling effect indicates how strong the significant effect was.

Table 6

Percentage Gain in Problem Solving Achievement

Group	Percentage Gain = mean gain / total score	Male	Female
Experimental	4.143 / 16 = 26%	4.813 / 16 = 30%	3.579 / 16 = 22%
Control	1.810 / 16 = 11%	1.667 / 16 = 10%	1.867 / 16 = 12%
Strategy Group	**% Gain**	**Male**	**Female**
Color VTN	4.8 / 16 = 30%	6.6 / 16 = 41%	4.0 / 16 = 25%
B/W VTN	2.5 / 16 = 16%	3.0 / 16 = 19%	1.3 / 16 = 8%
Writing	1.8 / 16 = 11%	1.7 / 16 = 11%	1.9 / 16 = 12%

Closer examination of the Table 6 summarizes the percentage of achievement gain in problem solving with respect to groups who used different strategies for learning science. The percentage gain in problem solving achievement was the highest (30%) for those students who used the color VTN strategies for learning science. Therefore, using color VTN strategies for learning science produces greater gains than black/white VTN and the writing strategy.

Generalizability of Learner Characteristics

The pre-post mean achievement gain analysis at the cognitive level of problem solving indicated that the use of the color VTN was a better learning strategy for male and female students with high abstract reasoning aptitude in addition to those male and female students with low spatial relations aptitude. Analysis of several data sets from the think-out-loud or interview-based design portion of the study, not reported in this paper, provides three additional sources of evidence for the transfer of the higher order thinking skill of problem solving for students with low abstract reasoning and spatial relations aptitude (Longo, 2001a). Although concept mapping is the most widely researched knowledge representation strategy few studies claimed efficacy of concept mapping for high ability students as did Pankratius (1990). Schmid and Telaro (1990) found out that lower reading ability concept mapping learners “performed as well as the higher reading ability learners” (p. 83).   Stevnsold & Wilson (1990) reported the concept mapping was not an effective strategy for the high verbal ability students. They suggested that “a longer-term study might allow these students to integrate concept mapping into their learning styles” (p. 479). This consideration of a “longer-term study” was one of the main parameters considered in the planning the design to test the efficacy of these VTN strategies. A meta-analysis study of nineteen concept mapping studies indicated that the length of time of students used concept mapping varied from .2 to 22 weeks (Horton, et al., 1993). For this inquiry, students constructed the VTN strategies over a five-month, or twenty-two week period.

Color as a Differential Cognitive Tool for Male and Female Students

Color VTN Female Students. Although gender differences with respect to science knowledge have been clearly established (Kahle & Meece, 1994; Parker, Rennie, & Fraser, 1996) few studies offer new cognitive tools to enhance achievement for female students. Females who used the color VTN strategies did not reach their male counterpart with respect to problem solving achievement. They did however enhance their problem solving achievement from two perspectives. First, they did move up the ladder and significantly surpass the males who used the black/white VTN and writing strategy, thus they were able to “shorten the shadow” (Parker, Rennie, & Fraser, 1996) between male and female achievement. Secondly, they did significantly improve their problem solving achievement when compared to females using the writing strategy.

The recent study by Jones *et al* (2000) indicated “gender-related patterns” with respect to how physical tools were used in the laboratory. These patterns were offered to help explain the differences in the way science knowledge is organized and constructed. One of the important findings from the Jones study indicated that “girls, more than boys, tended to exhibit relational orientations to the learning task…and this included an intimacy between self and tool” (p. 769). Gender influenced the choice of a VTN strategy (Longo, 2001). Females used significantly more color VTN strategies, while males utilized predominately black/white VTN strategies [Chi Square Value = 6.311 (df = 1), p = .012]. Other studies support these findings from the perspective of females having a larger color vocabulary Greene & Gynther, 1995). Tuman (1988) found that “female drawings incorporated a greater variety of color, used more harmonious color combinations, while boys used less color, tended to use color locally, and tended to used contrasting color combinations in their drawings” (1998, p. 140). The samples of networks in Appendices (1-5) demonstrate these different ways male and female use color and the physical space in their VTNs. Although an in depth discriminant analysis of the VTN drawings was not conducted as part of this study, visual inspection of the VTNs did show another distinct difference in the organization of the earth science knowledge on paper. Female VTNs were more symmetrical, balanced in organization, while male VTNs were less symmetrical. This difference in symmetry was also documented in Tuman’s research analyzing children’s drawings (1998).

Color VTN Male Students. Although fewer males chose to use the color VTN strategies for learning science, those that did had the greatest achievement gains in problem solving. Research in art education indicate that males tend to put down their colored pencils and pick up black/white pencils around the age of eleven to twelve (Burton, 1997). Findings from presented in this paper indicate that males should be encouraged to pick up those color pencils once again.

A New Interpretation on the Transfer of the Higher Order Thinking Skill of Problem Solving

Craik and Lockhart (1972) argued that the way we process information is responsible for the persistence in memory. The more deeply we process information, that is, the more we elaborate meaning with associations, images, and stories the more likely we will remember that information. Thus the color VTN students experienced a greater depth of processing by the nature of the elaborate construction of their networks. If the task of creating the networks were as students said, 'harder than writing' (Longo, 2001a) then more resources were being used by the student for this encoding process. Therefore the encoding is going to be deeper and richer, and it will be easier to recall.

The recent cognitive network theory of Kintsch (1998) supports this dimension of depth of encoding. The VTN strategy may require greater depth of information processing, that is, use more abstract reasoning, mobilizing conceptual knowledge more deeply, and for a greater extent of time than the writing tasks that utilize procedural knowledge. The writing strategy may not necessarily challenge the student to reorganize information in memory and differentiate networks of knowledge into more clearly delineated domains as during the construction of visual thinking networks.

According to Kintsch (1998) networks are a good model for representing knowledge and each node are propositions with linkages surrounding the propositions. For Kintsch meaning is then constructed in working memory by nodes being assembled accordingly to contextual demands. Procedural knowledge and various potential factors then further augment these nodes. The use of color in VTNs thus may create additional markers to the nodes, and make them more discriminable, and more of them retrievable from memory. A deeper processing can take place in working memory in a more complex and challenging demand on the individual by requiring students to go beyond the simple semantic representation involved during the typical procedural ways of dealing with knowledge as we write. By constructing VTNs, encoding is then enhanced since earth science knowledge is represented more deeply in terms of conceptual structures and contextual organization.

A New Perspective on a Theory Driven Model

In 1977, Novak argued in his book, A Theory of Education, that, "any attempt to advance a theory of education, must be firmly based in constructivism" (p. 23). That historical perspective gave rise to a "complete theory of education should eventually include a synthesis of neurobiological and cognitive scientific principles in addition to philosophical and cultural context" (Anderson, 1992, p. 1039). Edelman echoes this theme again in that "we must incorporate biology into our theory of knowledge and language" (1989, p. 239). The empirical findings and theoretical models from neurocognitive science as presented in the introduction of this paper, provide a foundation that explicitly constrains educational theory building. The problem solving achievement findings implicate a new metacognitive learning theory, the encoding activation theory of the anterior cingulate (Longo, 2001a).

One of the most important findings from the current neurocognitive research, as explained in the introduction of this paper and incorporated in the ENACT-AC model (see Figure 7, purple arrowhead lines) indicates that the streams that carry the distributed knowledge of color, shape, location, and motion from the occipital lobe of the visual cortex are maintained in the frontal lobe (Courtney, Ungerleider, Keil, & Haxby, 1996; Friedman & Goldman-Rakic, 1994; Smith, Jonides, & Koeppe, 1996; Wilson, Schalaidhe, & Goldman-Rakic, 1993). The frontal lobe region is the site of multiple working memory ensembles and is involved in the cognitive processes of planning, organizing, and decision making. These processes are used during problem solving. The working memory sites are also inter-connected to the temporal cortices where verb and word meanings meditate.

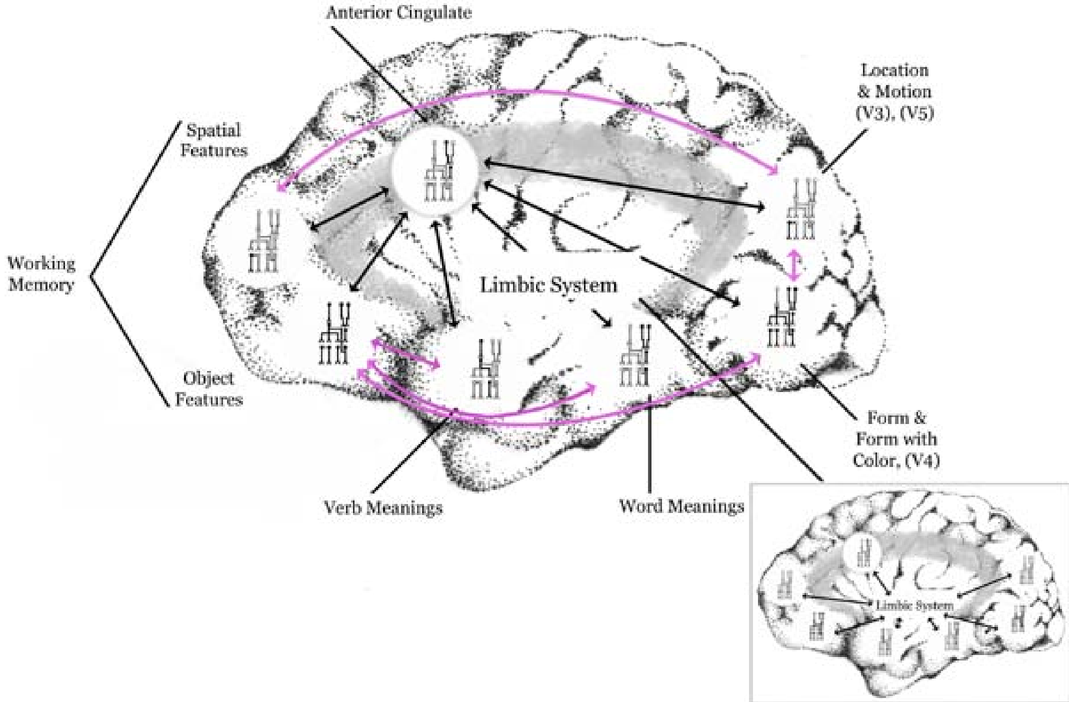

Figure 7. The encoding activation theory of the anterior cingulate, ENACT-AC (Longo, 2001a, p. 237).

The anterior cingulate has been hypothesized as an executive attention system (Posner and Raichle, 1994). This system helps to ensure that the processing in other brain regions is most efficient. Directing attention to color, activates many of the early visual cortices, V4, (Corbetta et al, 1991; Corbetta, Shulman, Miezin, & Petersen, 1995). The encoding of knowledge is most likely to be stable and recalled if it is given undivided attention and if this attention is directed to its meaning **(**Rugg, 1998; Brewer, Zhao, Desmond, Glover, & Gabrieli, 1998; Wagner, Schacter, Rotte, Koustaal, Dale, & *et* al 1998).

Theoretically, to solve a problem successfully students had to translate the words in order to represent the problem in working memory. The creation of an invention, a strategy, then is likely to be devised so that the conceptual knowledge can be used in a series of steps. Thus decisions had to be made as what to do next with this conceptual knowledge. (Gabel & Bunce, 1994). This process of invention was more extensive and elaborate for those students who used the color VTN strategies for learning science. This conclusion is supported by the problem solving strategy dimensionality evidence generated during the think-out loud interview based design (Longo, 2001a).

A greater number of co-associations could be formed between the occipital and temporal forms of distributed knowledge that connect to the frontal lobe as a result of the anterior cingulate mediating selective attending to color during the construction of the visual thinking networks (see Figure 7, black arrowhead lines). The ability to move around and re-activate the strengthened collective ensembles can be enhanced when the color VTN learner was reconstructing knowledge in working memory during problem solving.

Color as knowledge in the brain, is more than an anatomical marker found in the association visual cortex, (V4). The neural connections from this site are maintained through the regions of the prefrontal cortex. Color, as knowledge in the brain is an integral, cross-modal, associative component within the widely distributed neuronal memory networks of the cortex. These color associations are defined by the neural relationships activated in the cortical networks during three stages: the perceptual stage, the attentional stage (encoding) and the retrieval stage of working memory.

Recommendations for Future Research

Since Ault states that “transfer of problem-solving skill is elusive and the interaction of domain-specific knowledge with strategic knowledge in problem solving is complex, differing, perhaps, from discipline to discipline in substantial ways” (1994, p. 280), any study that offers such strong claims of enhancing problem solving achievement as presented in this paper needs to be replicated. We invite other science educators to initiate studies utilizing this new learning strategy in a wide variety of science domains.

As previously stated in the methodology, students were randomized into the experimental and control groups. A causal relationship was clearly established between the use of VTN strategies (color and black/white) with respect to problem solving achievement. Since students were allowed to choose and switch to either black/white or color VTN strategies for learning science during the twenty-two weeks of treatment, a newer study needs to be conducted that randomly assigns students to two groups for learning science. The pre-post problem solving achievement study can then be replicated with experimental group representing the color VTN group and the control group being the black/white VTN group. Findings from this new study would test for the presence of a causal relationship between color VTN strategies and problem solving achievement thus affirming the inter-relationships found between the utilization of color VTNs and positive changes in the learners’ knowledge base (Longo, 2001a).

Gender differences need to be explored further with respect to how students use the the VTN as a new cognitive tool. A longitudinal study comparing the developmental changes in network construction between males and females may contribute new insights on the differential nature of knowledge building.

Would these problem solving achievement results be replicated if students constructed computer generated networks? That is, what role does the reflective process of physically constructing the knowledge structure as the components of a VTN influence learning as compared to machine-based construction?

Summary

The metacognitive process of encoding science knowledge into visual thinking networks transfers to the improvement of problem solving achievement. The use of color enhances this transfer mechanism especially for female students. This new learning strategy was conceptualized from current neurocognitive science. Languis and Miller (1992) argued that "before substantial change can occur in education, the wide gap between neurocognitive science and classroom practice must be closed" (p.493). The findings and claims reported in this paper not only begins to close this gap, but offers two new bridges: visual thinking networking, a metacognitive learning strategy for the representation of science knowledge, and the ENACT-AC theory. Both of these bridges integrate neurocognitive science to the educational domain of metacognitive learning. The ENACT-AC model represents a new dimension in building a learning theory that is explicitly constrained by current neurobiology and neurocognitive science.

The new understanding of the role of the visual cortex in cognitive processing has strong implications for broadening the science education research agenda with respect to research questions, methodology, and foci. The claims generated from this phase of the experimental design provide insight into the importance of providing student choice when integrating multiple ways of thinking about science concept formation.

Educationally the role of the senses becomes a focus with respect to concept formation. What is critical for classroom experiences is to have a diverse number of multi-modal (sensory) learning tasks for the acquisition, representation, and assessment of knowledge. These multi-modal experiences will continue to strengthen the internal connections between the brain's distributed forms of knowledge. Perhaps assessment then can be view authentic with respect to the modality in which the learning experience occurred.

Visual thinking networking strategies encourages learners to choose meaningful color and symbolic visualizations to the scientific concepts, processes, and experiences into a coherent whole. In doing so, we encourage a broadened epistemological view of color as knowledge. This view supports Eisner's arguments for "a transformation of the ways in which we teach, the curriculum resources we employ, and the forms we allow students to use in order to represent what they have come to know" (1994a, p. 87).

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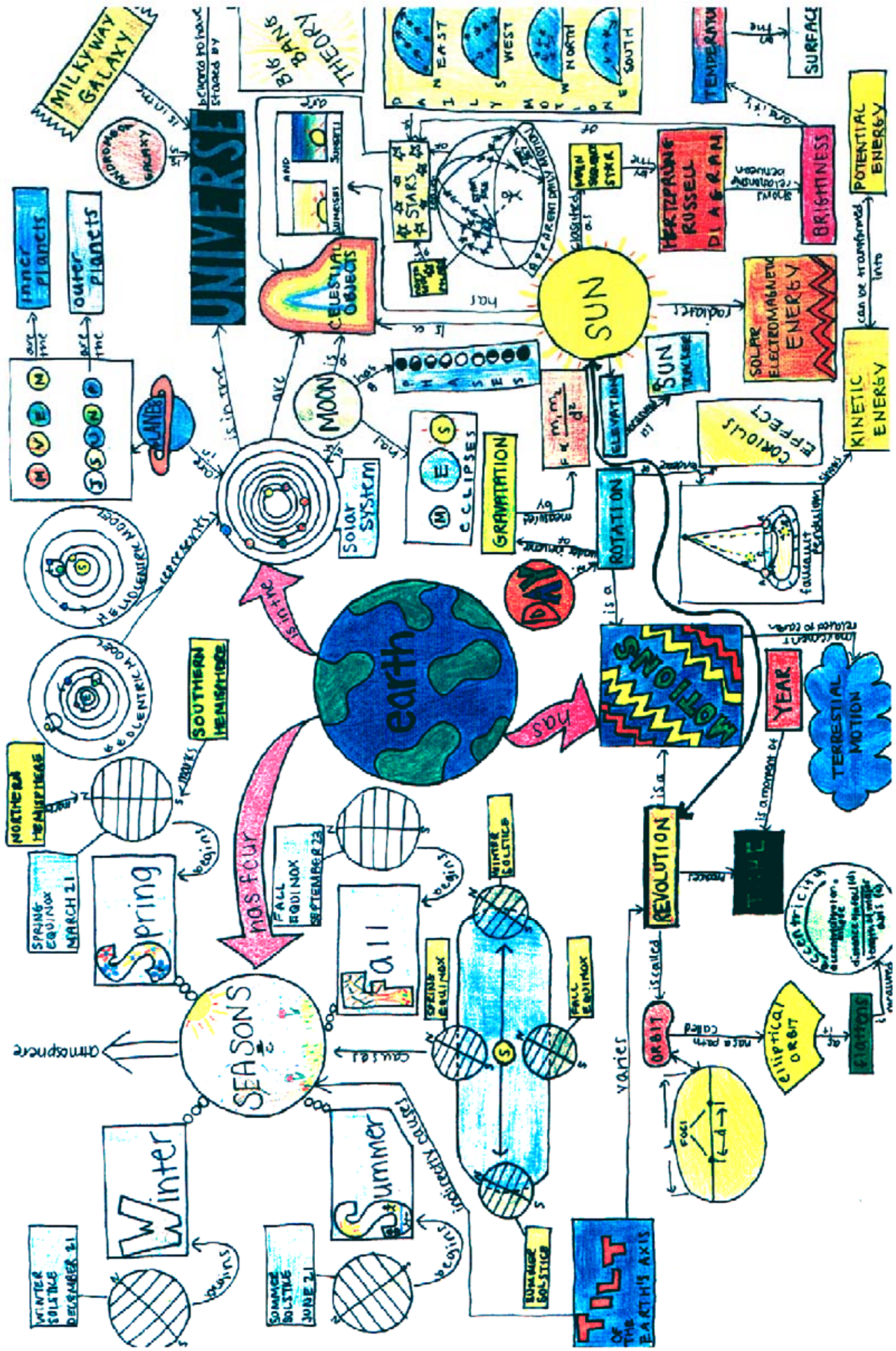
About the Authors…

Palma J. Longo, is an Assistant Professor of Biology at the University of Massachusetts Dartmouth. She teaches science curriculum methods at the elementary and secondary level and is an instructor for the freshman Biology of Organsism Laboratory. She continues to research the role of color in metacognitive learning through the use of visual thinking networks.

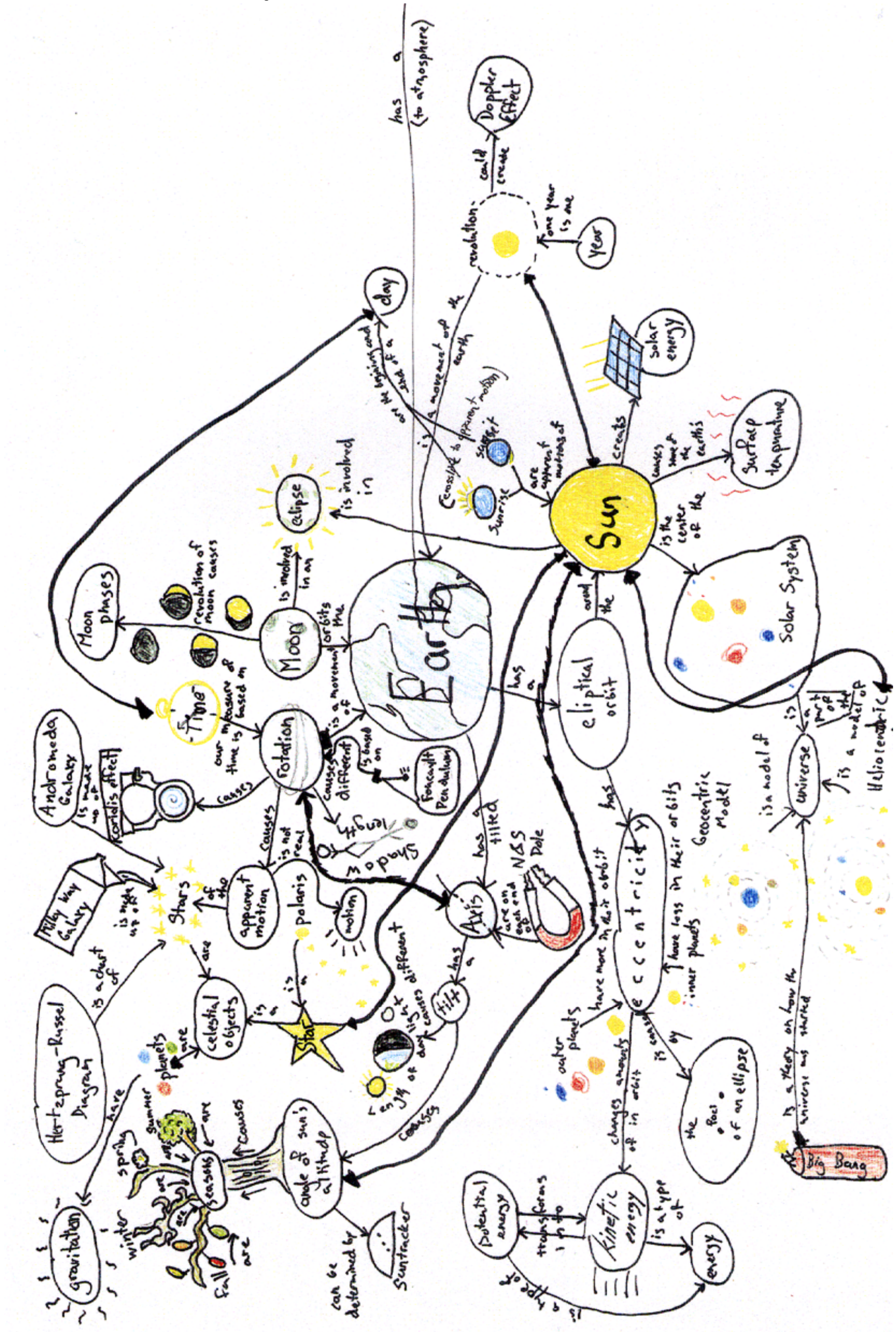
O. Roger Anderson, is Professor and Chair of the Department of Mathematics, Science, and Technology at Teachers College and Senior Research Scientist in biology at Columbia University. He teaches a course in neurocognitive models in addition to courses in biological science and does research on the physiological ecology of eukaryotic micrroganisms as well as cognitive aspects of teaching and learning in science.

Paul Wicht, is a science teacher at Byram Hills High School in Armonk, New York. His discipline expertise is in the earth and environmental sciences.

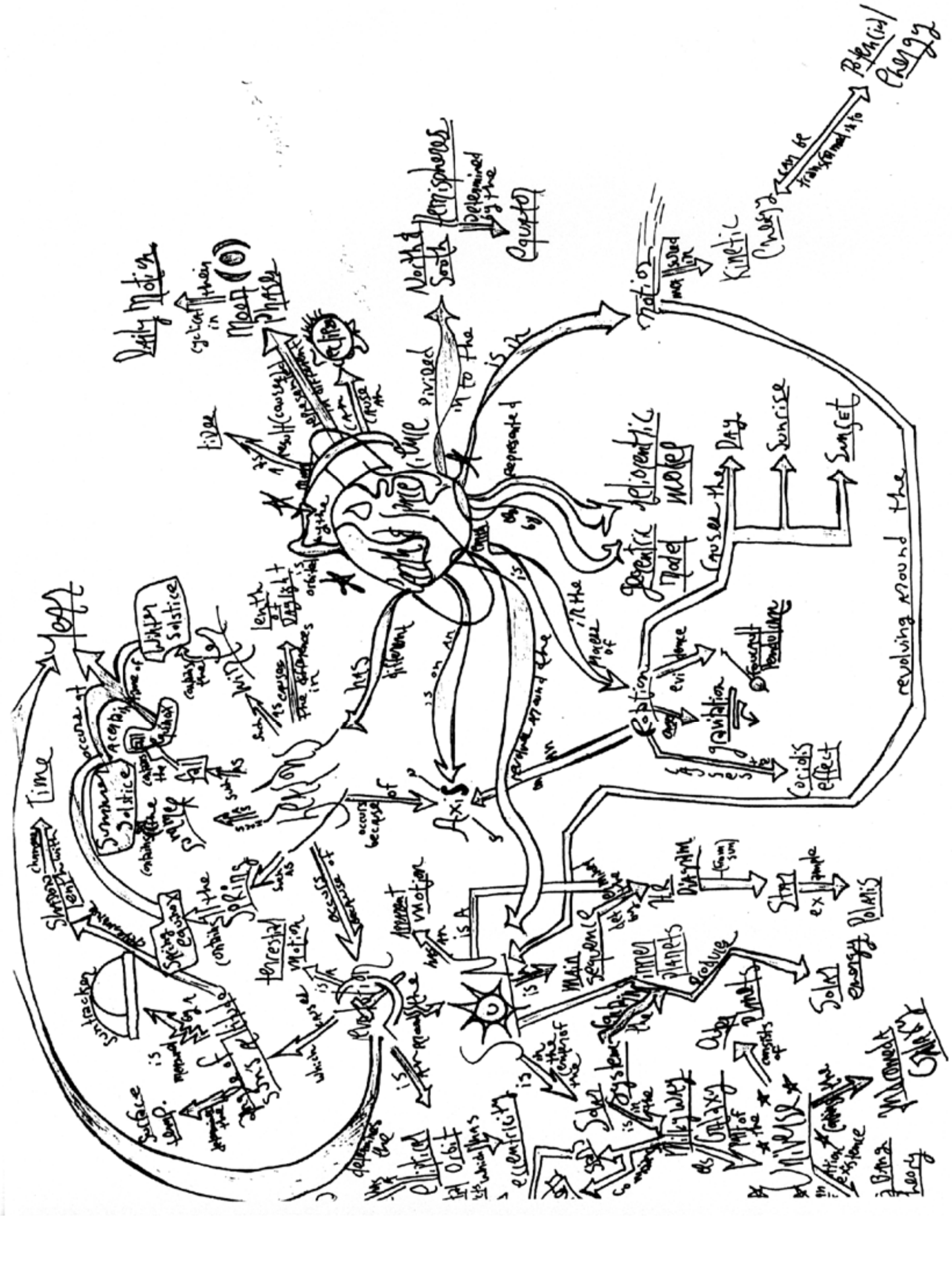
Appendix 1: A network (Level 4)of semantic labels in color with symbolic images constructed by a female.



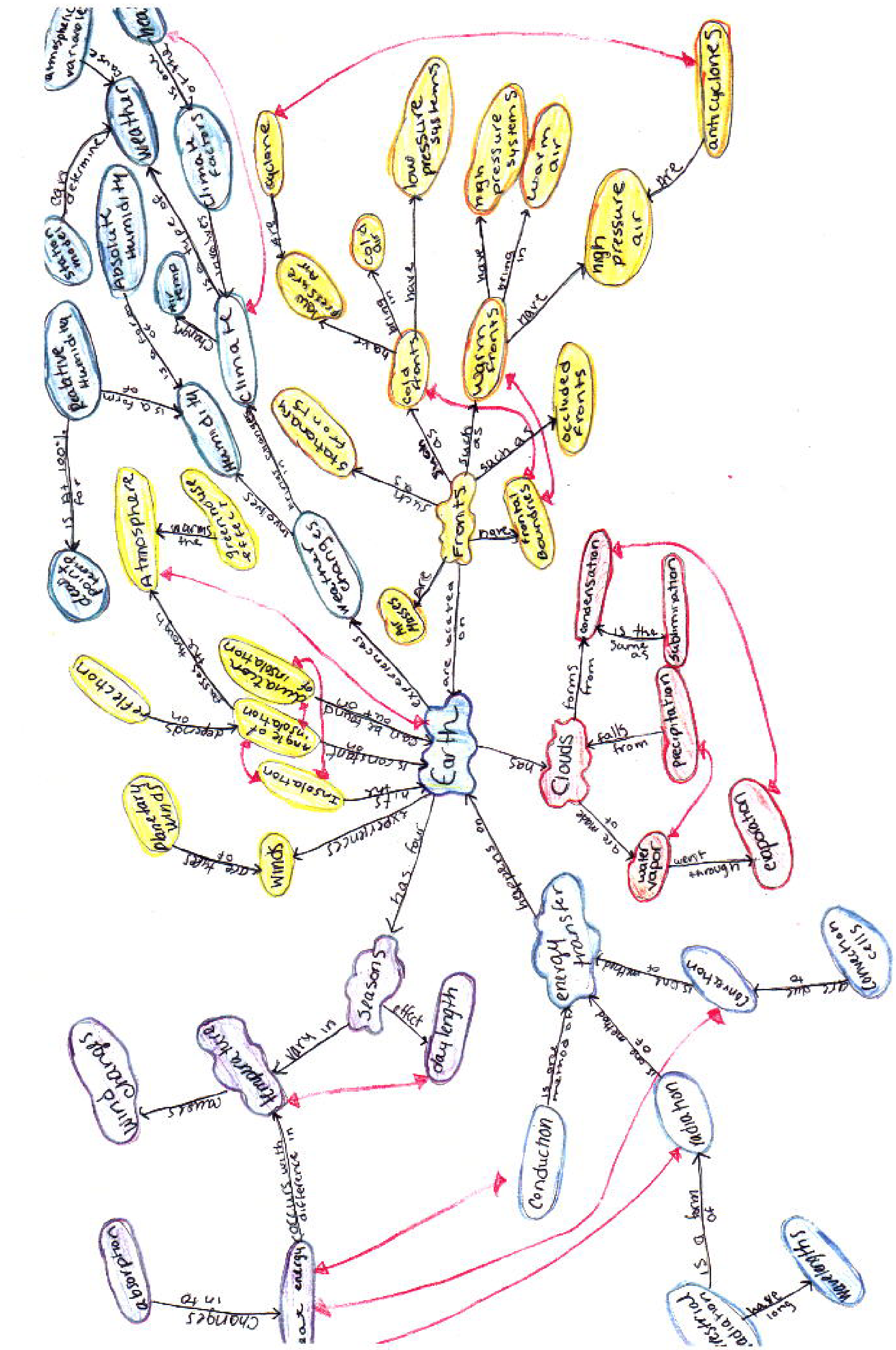
Appendix 2. A network (Level 4) of semantic labels in color with symbolic images constructed by a male.



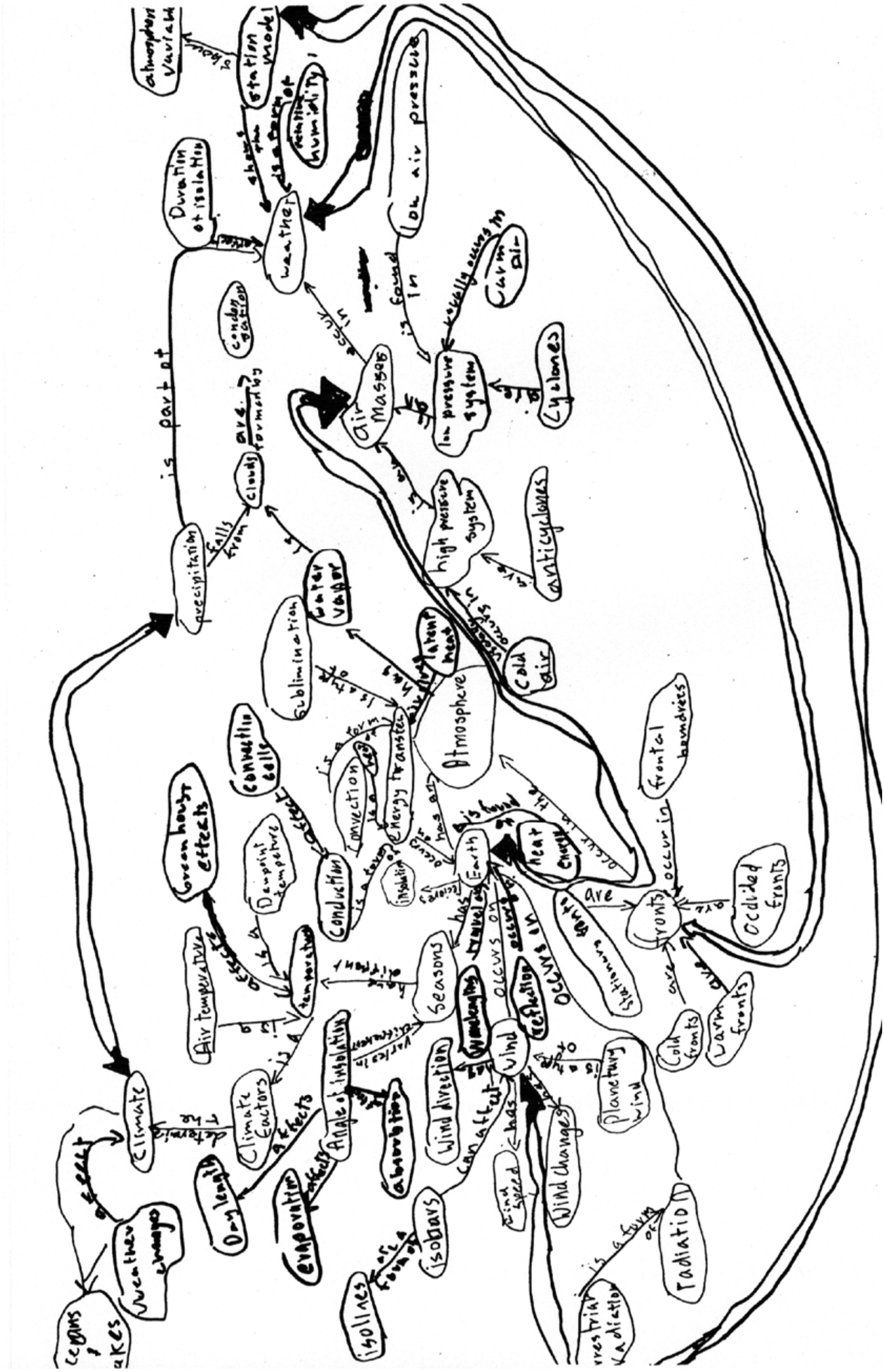
Appendix 3. A network (Level 3) of semantic labels in black/white with symbolic images constructed by a male.



Appendix 4: A network (Level 2) of semantic labels in color constructed by a female.



Appendix 5. A network (Level 1) of semantic labels in black/white constructed by a male.



Appendix 6

Theory Driven Knowledge Representation Strategies

Date	Strategy Name	Developer of Strategy	The Product of Constructed Knowledge	Theoretical or Conceptual Framework Grounding the Knowledge Representation Strategy
1975	Active structural networks	Norman & Rumelhart	Concept nodes[1] illustrate processes of change in events and objects connected by arrowheaded linking lines[2] that use verbs, prepositions or nouns.	Rumelhart's connectionist theory
1979	Concept mapping	Stewart, VanKirk, & Rowell	Hierarchical display of concept nodes linked by a line.	Ausubel's meaningful learning theory and theory of knowledge subsumption (knowledge is arranged hierarchically in memory.
1979	Networking	Holley, Dansereau, McDonald, Garland, & Collins	Hierarchical display of prose material. Nodes contain paraphrases and image of key ideas and concepts linked by an arrowheaded line[3] or arc.	Quillian's network model of human memory.
1979	Mind mapping	Buzan	One concept node is the focal point; other concept nodes linked with noun and unlabeled lines; use of color, and symbolic representations.	Right/left brain hemisphere paradigm
1980	Semantic webbing	Freedman & Reynolds	One concept label or phrase idea is the focal point. Other concept nodes linked with unlabeled lines.	Bruner's theory of conceptual thinking; Instructional design models of Henry & Gerhard.
1981	Concept mapping (revision of 1979 concept mapping)	Novak	Hierarchical display of concept nodes linked with verbal or prepositional lines; crosslinks[4].	Ausubel's meaningful learning theory and theory of knowledge subsumption (knowledge is arranged hierarchically in memory).
1983	Clustering	Rico	One concept node is the centering point. Other concept nodes are linked with unlabeled lines.	Right/left brain hemisphere paradigm
1987	Concept circles	Wandersee	Concept labels embedded within inclusive, exclusive, and overlapping circles.	Set theory

1990	Semantic networking	Fisher	Computer generated; one concept node is the focal point. Concept nodes linked with verbal links; crosslinks.	Quillian's theory of human memory.
1990	Computer generated associative network	Schaveveldt	Pathfinder software defines networks by generating concept pairs.	Graph theory
1990	Knowledge mapping (revised name from 1979 networking)	Dansereau & Cross	Node to node assemblies; with arrow-headed links to specify the nature of the relationship. Relationship between nodes: part, type, characteristic, leads to, next, example, and comment.	Quillian's network model of human memory
1995	Contextual mapping	Bloom	Children's depictions of images, metaphors connected to concept labels; some connecting lines use verbs.	Context of meaning
1996	Thinking maps	Hyerle	Integration of 8 graphic forms of thinking processes.	Common visual language
1997	3-D concept mapping	Farrokh	Computer generated 3-D concept map.	Rumelhart's connectionist theory
2001	Visual thinking networking	Longo	Once concept node is the focal point. Other concept nodes linked with arrowhheaded verbal lines; use of color and symbolic respresentations; use of arc, bidirectional lines and cross links.	Zeki's theory of functional specialization of the visual cortex; Reconstruction of distributed knowledge in memory.

A concept node is a single unitary concept.
Each link is a single relation between two nodes.
Arrowheaded lines or arcs are directional links that specify the nature and the direction of the relationship between the two nodes.
Crosslinks are directional links between different parts of representation to indicate a share relatedness.

Appendix 7.

Concepts used in the first VTN and writing strategy Topic: Earth & Space Science

earth	summer	Big Bang theory	inner planets
sun	moon	day	star
motion	fall	spring	winter
time	rotation	winter solstice	summer solstice
stars	suntracker	apparent motion	spring equinox
eclipse	revolution	terrestrial motion	elliptical orbit
latitude	rotation	Hertzprung-Russsell	Doppler effect
axis	velocity	planet period	focus (of an ellipse)
sunrise	sunset	23.5 degree tilt	outer planets
Polaris	planets	parallelism of earth's axis	gravitation
eccentricity	moon	N & S hemisphere	Coriolis effect
tides	seasons	Foucault pendulum	shadow length
universe	solar energy	angle's of sun altitude	moon phases
	fall equinox	kinetic energy	surface temperature
		length of daylight	heliocentric model
		potential energy	geocentric model
		solar system	main sequence

Appendix 8. Guidelines for constructing a visual thinking network

As described in our workshop, a visual thinking network (VTN) is a vehicle or strategy for meaningful learning whereby you describe your understanding of a particular topic. A network is created by connecting (linking) one concept to another. You can choose and change to any of the four types of VTNs:

- VTN Level 1 – A network of conceptual labels in black/white.
- VTN Level 2 – A network of conceptual labels in color.
- VTN Level 3 – A network of conceptual labels with black/white symbolic or pictorial images.
- VTN Level 4 – A network of conceptual labels with color symbolic or pictorial images.

You will be creating three VTN sets over the next several months, one for each major topic you will be studying: (1) Earth and Space Science, (2) The Atmosphere, and (3) Oceans, Solid Earth, and Earth's History.

Characteristics of a Good VTN

Since VTNs are an individual's representation of their meaning making, different people construct different VTNs on the same topic. Here are some general characteristics to all well-constructed VTNs.

1. A VTN is created around one focal or centering point. This focal point need not be "centered" in the middle of the paper. The placement is up to you and what meaning you are constructing with it's placement in the VTN.

2. Several main branches emerge from the centering point that describe main ideas. Sub-branches are created from these main branches.

3. The unit of knowledge construction is the concept. These concepts are usually nouns, a single idea about an object or event, that you generated either from a brainstorming session or the chart you created from the resources you have been working with. Each concept is enclosed within some form or shape.

4. Related concepts are connected to another. This relationship is formed by placing linking words on the top of an arrow-headed line. These linking words are usually verb, verb phrases, adverbs or prepositions, and prepositonal phrases. Each concept appears only once in the VTN.

5. The direction of the arrow to and from a concept describes the nature of the relationship you are expressing.

6. Different types of links can be used to express different relationships such as a hierarchy, chain, cluster, and recursive. (Refer to handout 'Making Connections' that describe these four different types of relationships.

7. The use of color is encouraged to help facilitate the encoding of knowledge into memory. Color may be used to distinguish different levels of concepts or ideas you are trying to express.

8. The use of symbolic representations, images, or metaphors are encouraged to show the multiple ways of expressing concept formation.

9. Crosslinks are used to show relationships between concepts in different parts of the network. Crosslinks are created in a particular color to distinguish them from arrow-headed linking lines. Cross links are bi-directional arrows.

Constructing your VTN

1. Be patient…. this is a new strategy you are learning how to use. One in which you are being asked to think about your thinking. There is not "right" way to construct a VTN. Remember this network will show your understanding and development of different science topics.

2. Materials you need:

- a concept list
- 11 x 17 paper
- pencils and colored pencils
- index cards and scissors

3. Start with your concept list. It has been helpful for some people to put these concepts on smaller pieces of paper (cut-outs of concept labels) so you can move them around on the large piece of paper.

4. Look at your concept labels..
   - Do any of these concept labels act as a focal point?
   - Do any of these concept labels act as main branches?

5. One way to begin to is to group related concepts. These groups of concepts share a similar relationship. As you are moving these concept labels around ask yourself:

   What is the criteria, the decision, that was made for a concept label to be a member of this group? Write down this criteria. This criteria may become and other concept label.

What type of network link (hierarchy, chain, cluster, or recursive) can you use to express the nature of the relationship between these grouped concepts?

6. Networking is a process and you may develop several "working VTNs" until you have the one that expresses your understanding of the concepts in the topic. For example you may choose one concept label as the focal point of your first VTN draft then change to a different focal point as you begin working through the nature of the relationships you want to express. (SEE EXAMPLES)

7. *Can you identify one focal point?* Place this concept label on your large piece of paper and enclose it with some shape and color.

8. What concepts do you want to branch from this point?

10a. *What relationship do you want to express connect the focal point to the main branches?* Write the linking word on the top of the arrowheaded line.

b. What is the direction of the relationship? What concept is the arrowhead line pointing to?

11. Continue to link all the concept labels you have on your list.

12. When finished ask yourself: *In what ways does this VTN show my understanding of the topic?*

Appendix 9. Writing Strategy Guidelines

What is a Science Writing Project?

Scientific concepts are usually nouns that describe events and objects in our environment. One way to show you understanding of how these events and objects are related to one another is to give a voice to the scientific concepts. There are many ways to give a voice to a particular set of concepts: writing a play, a short story, free verse poems, a rhyming poem, writing a commercial or a script for a cartoon or a web site script.

An Example of student writing project:

Here is an example of a rhyming poem. The words in bold print are the scientific concepts that needed to be used.

A Voice for Physical Science

Just before reality began
The **Universe** was in short span.
Enter the **Big Bang** with all its strength,
To make **Space** long in length.
First come **elements,** then come **gases**,
And then come materials for all the **masses**.
All swirl into some shape or form,
And at the end of the primeval storm..
WE HAVE A **SOLAR SYSTEM**.

Materials you need

- Concept List
- Index cards
- scissors
- pencil

Suggestions for Your Writing Project

1. Start with your concept list. It has been helpful for some people to put these concepts on smaller pieces of paper (cut-outs of concept labels) so you can move them around on the large piece of paper.

2. Next you need to decide what form of writing project you will use. A good starting point is to look at the list of concepts. You may want to ask yourself the following questions:

   - *Can these concepts be used a play characters?*
     Can these concepts be used in poem.. short story.. or commercial?

3. Group the concepts on the basis that they share a similar relationship. Some concepts are more related to others. As you are moving the concepts around ask yourself, what criteria am I using to place this concept into this group? The answer to this question may help you to decide how many different sequences you may want to use in the writing project.

4. Remember the voice you create is your meaningful understanding of the relationship between the different concepts.

Appendix 10 Descriptive Statistics between groups who utilized different strategies for learning science

Cognitive Level	VTN Levels	Gender	Mean	Std. Deviation	N
Gain score: fact	Color VTN	female	4.3125	1.9568	16
		male	4.7500	2.3755	8
		Total	4.4583	2.0637	24
	B/W VTN	female	3.6667	1.1547	3
		male	3.7500	1.6690	8
		Total	3.7276	1.4894	11
	Writing	female	4.4000	1.9567	15
		male	4.8333	1.7224	6
		Total	4.5238	1.8606	21
	Total	female	4.2971	1.8673	34
		male	4.4091	1.9735	22
		Total	4.3393	1.8808	56
Gain score: concept	Color	female	4.0625	3.6418	16
		male	4.7500	2.8661	8
		Total	4.2917	3.3555	24
	B/W VTN	female	4.0000	2.0000	3
		male	3.1250	2.9790	8
		Total	3.3636	2.6560	11
	Writing	female	4.0667	3.5146	15
		male	3.0000	3.8987	6
		total	3.7619	3.5624	21
	Total	female	4.0588	3.3929	34
		male	3.6818	3.1530	22
		total	3.9107	3.2768	56
Gain score: rule/principle	Color VTN	female	1.3750	1.4549	16
		male	2.6250	1.0607	8
		Total	1.7917	1.4440	24
	B/W VTN	female	2.6667	1.5275	3
		male	2.0000	.7559	8
		Total	2.1818	.9816	11
	Writing	female	1.2000	1.5675	15
		male	1.3333	1.6330	6
		Total	1.2381	1.5461	21
	Total	female	1.4118	1.5199	34
		male	2.0455	1.2141	22
		Total	1.6607	1.4305	56
Gain score: problem solving	Color VTN	female	4.0000	2.0331	16
		male	6.6250	.9161	8
		Total	4.8750	2.1328	24
	B/W VTN	female	1.3333	1.5275	3
		male	3.0000	1.9272	8
		Total	2.5455	1.9164	11
	Writing	female	1.8667	2.6150	15
		male	1.6667	2.9439	6
		Total	1.8095	2.6358	21
	Total	female	2.8235	2.4921	34
		male	3.99545	2.8532	22
		Total	3.2679	2.6760	56