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Results and Implications of a 12-Year Longitudinal Study of Science Concept Learning

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Abstract

This paper describes the methods and outcomes of a 12-year longitudinal study into the effects of an early intervention program, while reflecting back on changes that have occurred in approaches to research, learning and instruction since the preliminary inception stages of the study in the mid 1960s. We began the study to challenge the prevailing consensus at the time that primary school children were either *preoperational* or *concrete operational* in their cognitive development and they could not learn abstract concepts. Our early research, based on Ausubelian theory, suggested otherwise. The paper describes the development and implementation of a Grade 1–2 audio tutorial science instructional sequence, and the subsequent tracing over 12 years, of the children's conceptual understandings in science compared to a matched control group. During the study the concept map was developed as a new tool to trace children's conceptual development. We found that students in the instruction group far outperformed their non-instructed counterparts, and this difference increased as they progressed through middle and high school. The data clearly support the earlier introduction of science instruction on basic science concepts, such as the particulate nature of matter, energy and energy transformations. The data suggest that national curriculum standards for science grossly underestimate the learning capabilities of primary-grade children. The study has helped to lay a foundation for guided instruction using computers and concept mapping that may help both teachers and students become more proficient in understanding science.

Key Words: audio-tutorial instruction, cognitive development, energy transformation

One of the issues debated in the early 1960s was the extent to which children could profit from instruction on abstract, basic science concepts such as the nature of matter and energy. The dominant thinking in science education and developmental psychology was centered on the work of Jean Piaget, particularly his ideas about cognitive operational stages. Piaget had devised some ingenious interviews administered to children, the results of which could be interpreted to support his theory of stages of cognitive operational development. It was widely assumed that children could not profit from instruction in such abstract concepts as the nature of matter and energy before they reached the formal operational stage of thinking at ages 11 or older. On the other hand, these ideas were challenged by contemporary work, particularly for us by Ausubel's (1963) assimilation theory of learning. The fundamental questions that concerned me and my research group at Cornell University were:

1. Are these claimed cognitive operational limitations of children the result of brain development, or are they at least partly an artifact of the kind of schooling and

socialisation characteristic of Piaget's subjects, and those commonly tested in US and other schools?
2. With appropriate instruction in basic science concepts such as the nature of matter and energy, can 6–8 year-old children develop sufficient understanding to influence later learning?
3. Can the development of children's understanding of science concepts be observed as specific changes in their concepts and propositions resulting from the early instruction and from later science instruction?
4. Will the findings in a longitudinal study support the fundamental ideas in Ausubel's learning theory?

Answers to these questions could only be obtained by first designing systematic instruction in basic science concepts for 6–8 year-old children, and then following the same children's understanding of these concepts as they progressed through school, including later grades when formal science courses were taken. This was the instructional development and research project we set out to do.

The principal principle of the Ausubelian learning theory we considered in the design of our instruction comes from the epigraph to his 1968 book:

> If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.

Development of Instructional Materials

Instruction in our longitudinal study was by means of audio-tutorials, in which children learned from audiotapes that we had developed and that were supplemented with film clips and equipment. The audio-tutorial lessons were based on ideas in the National Science Teachers Association report, *Importance of Conceptual Schemes for Science Teaching* (Novak, 1964), and an elementary science textbook series, *The World of Science* (Novak, Meister, Knox, & Sullivan, 1966).

Table 1 gives titles for the 28 lessons that were offered on a schedule of approximately one new lesson installed in a classroom every other week. It is evident from the titles that the content of these lessons was far beyond the usual concepts presented in grades 1 and 2 (6–8 year-olds). It is also evident that concepts other than those dealing with matter and energy were presented, but after the first year of the study, due to time and resource limitations, we interviewed children on the understanding only of molecular kinetics ideas.

As my graduate students and I developed an idea for a new lesson, we would interview six to eight primary grade children in an open ended interview, usually using some of the "props" we were planning to use to teach the central concepts of the lesson, such as pictures, materials to be manipulated, loop films, or apparatus we were considering. These interviews gave us some idea of what anchoring concepts

Table 1
Titles for 28 Audio-Tutorial Lessons Used in Grades 1 and 2 in Our 12-Year Study.

1.	Classification of objects by their size, shape and weight
2.	Classification of batteries: Some batteries can cause a bulb to light and others cannot
3.	Batteries are a source of electric energy: Electric energy can cause a bulb to change
4.	Electric energy is involved in many kinds of changes
5.	Whenever you notice a change, you know energy is involved
6.	Differing amounts of change occur when more energy or less energy is involved
7.	Energy can be stored and involved in future changes
8.	People use energy and change themselves and other things
9.	There are some ways in which all animals are alike
10.	Moving and growing are changes: All animals use energy from food to change
11.	Different animals eat different kinds of food
12.	Growing plants need air, water, and light
13.	Living seeds change in certain ways
14.	Growing is a kind of change in plants and animals
15.	A comparison of plants and animals
16.	Nothing changes by itself
17.	Air is real; air causes changes
18.	Some distinctive features of solid things, liquid things, and air
19.	Things are made of parts
20.	All solid things can be thought of as made of tiny parts. These little things can be called molecules
21.	All liquid things and air can also be thought of as being made of little parts called molecules
22.	Wind and air demonstrate the movement of molecules of air
23.	All molecules are constantly moving around
24.	The molecules of a solid do not move around freely, while molecules of liquid move more freely, and the molecules of air move most freely
25.	Classification of materials
26.	Changes and things that cause them
27.	Energy is involved in all changes
28.	Energy is involved in changes that can be measured

most of the children already had, and also gave some preliminary feedback on how they were interpreting or using the props. This process was often repeated several times, and again after lesson prototypes were developed. On average, each lesson underwent six to eight revisions before it was deemed ready to use in classrooms. We also considered Ausubel's ideas of *progressive differentiation* and *integrative reconciliation* in designing the lessons and lesson sequences (see the section on concept mapping for further discussion of these ideas). The idea of progressive differentiation requires that students build upon their prior relevant concepts, and elaborate concepts in earlier audio-tutorial lessons in a sequence as they study later related lessons.

This required that some students needed to experience earlier lessons in a sequence before we could use these students to help develop later lessons. Furthermore, many concepts were revisited in later lessons, but with different examples or props to effect greater differentiation of concepts introduced earlier, and thus also to achieve integrative reconciliation of concepts that may have been initially confusing to a child or where meanings acquired may have been somewhat distorted. It is evident from the lesson titles that certain concepts were revisited in multiple contexts. Photos and loop films were selected or constructed in many cases to serve as *advance organisers*. That is, we would use things that were familiar to the students, and we would build on the familiar to point them to see new aspects or dimensions of the new materials observed, much of this through the audio guidance.

There was great teamwork in the development of the lessons, and conversations about lessons often dealt at some length on the degree to which the lessons satisfied Ausubelian principles. Some of the graduate students designed lessons to use in their own thesis research work, and we adapted some of these lessons to use in our longitudinal study. Perhaps the best known of these lessons in the science education community were lessons dealing with the planet Earth and gravity developed by Joseph Nussbaum (Nussbaum & Novak, 1976). The development of the audio-tutorial lessons actually continued after we began our longitudinal study, primarily for individual graduate student research projects. As the longitudinal study progressed, desktop computers began to become available and we saw that in time computer mediated instruction could be much superior to audio-tutorial instruction. With the advent of the Internet and much more powerful and reasonably priced computers, this became the direction in which our work moved. Nevertheless, the lessons learned in developing the audio-tutorial program have been very valuable in the design of our current and planned computer-mediated instructional programs. One of the aspects that proved to be useful was to refer constantly to the theoretical ideas that guided our lesson development and evaluation.

In the longitudinal study, the lessons formed part of the program in 5 of 13 elementary schools in Ithaca, New York. The 5 schools were representative of Ithaca schools. Our initial work in developing the audio-tutorials had become familiar to the teachers, and we had no trouble in enlisting their collaboration with our research. School administrations were also supportive. The teachers did not, however, take part in the program other than to allow their students to work with the audio-tutorial materials. While it would have been desirable to have the teachers work with their students in related projects and in class discussion, we did not have the resources to train the teachers in the science that they would need to do this effectively. We asked teachers not to supplement the audio-tutorial lessons with their own materials and discussion, partly to provide the same level of instruction to all audio-tutorial students in the study, but also because we found during lesson development that teachers' discussions often introduced misconceptions and other errors in content. Ideally, teachers would play an active role in the science instruction in conjunction with the audio-tutorial lessons, but we did not find this to be possible with our study and resource limitations.

Methodology of the Study

All first-grade classes in the 5 participating schools were given audio-tutorial instruction during the first year, 1971/72, and all second-grade classes in the same 5 schools were given audio-tutorial lessons in the second year. There were initially 191 students in these classrooms, and 156 in grade 2 after the loss of students who had moved after grade 1. It was not feasible to divide classes at random into two groups. We chose the alternative of using as a "control" group students in the same schools, with the same teachers in the same classrooms, but beginning one year after the lessons were given in these classrooms. Thus we held essentially constant the instructional setting and the population sampled for the students who received the audio-tutorial lessons in the first and second years, and those in the same classrooms who did not receive these lessons in their first and second years of schooling which were the second and third years of our study. We called the students who had two years of audio-tutorial lessons the *Instructed* students, and those who followed a year later in the same classrooms but without the audio-tutorial lessons the *Uninstructed* students. However, we could not manage, with our limited resources, to interview an equal number of Uninstructed students, so we chose only a subset of 48 students at random from the Uninstructed groups. This method of sampling also helped with interview logistics, since Uninstructed students were interviewed a year later than Instructed students. Figure 1 shows a timeline for the project, beginning with the initial development of audio-tutorial lessons in 1965 to publication of the results from the project in 1991.

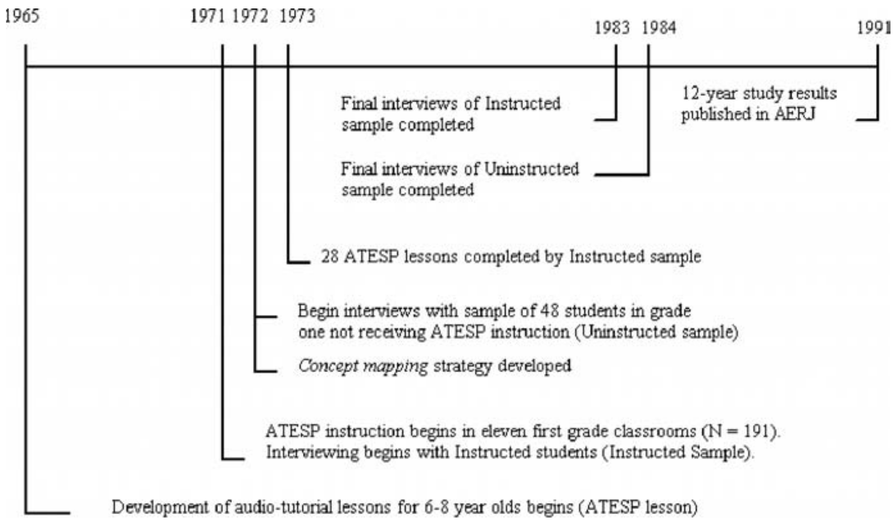


Figure 1: Timeline for the project.
ATESP: Audio Tutorial Elementary Science Program.

The lessons were placed in carrel units, usually in a corner of the classroom. The class teacher determined the time provided for student involvement with the lessons, but most often this was during "seat-work" times, or when the teacher was working with small reading groups. Students, one at a time, could take turns doing the audio-tutorial lesson. Some students observed others doing the lessons, and many students repeated lessons one or more times, often during recess, lunchtime, or other free time. Each lesson required approximately 20 minutes for a student to complete; thus the 28 lessons provided some 10–20 hours in carefully designed instruction over the two-year span of the instruction. Those teachers who included science in their instruction (a minority) usually dealt with topics such as seasons, clouds, and plant growth, but only in a descriptive manner and not including the basic science concepts such as energy transformations and the particulate nature of matter.

Each teacher we worked with reported excellent student response to the audio-tutorial lessons, and some of the teachers also noted their value for their own learning. None asked to be dropped from the study and most wanted to continue to use the lessons in future years.

Early in the study we developed various forms of paper and pencil tests, including tests with pictures that students marked with crayons following oral questions. We found in subsequent interviews with children that these paper and pencil tests were not valid indicators of the conceptual understanding of students. We subsequently chose to use modified Piagetian interviews as primary evaluation tools, with procedures as described elsewhere (Novak & Gowin, 1984, Chapter 7).

We designed interviews that used some of the materials that were in the lessons and other materials that were different but illustrated the same concepts. We prepared interview kits, and these were used by a number of different graduate students, with some instruction in how to do the interviews. Interviews were done with the Instructed students several times during the first year, including interviews on topics other than the nature of matter and energy. However, we found we did not have the staff resources to continue interviewing all Instructed and Uninstructed students on several domains of science, and chose to interview students only on concepts of matter, energy, and energy transformations. The same interview kits were used as the students progressed through school, and over the years. We also did not have staff to interview all students each year, and we had to choose a random sample from the Instructed and Uninstructed groups for later years of the study. All interviews were tape-recorded and some were also video-recorded. The number of students interviewed each year is shown in Table 2. Ithaca has two junior high schools (grades 7–9) and one high school (grades 10–12). This made it easier to do follow-up interviews, especially in their high school years. We made a concerted effort to interview all students remaining in both the Instructed and the Uninstructed samples during their senior year and succeeded in interviewing 85 of the 87 students remaining in high school. Many children have parents who are students at Cornell or Ithaca College, and they leave Ithaca when their parents complete school. With the high attrition rate, we were perhaps a bit lucky that the remaining Instructed and Uninstructed students

Table 2
The Interview Timeline: Numbers of Students Interviewed.

Interview cycle	Instructed number	Dates	Uninstructed number	Dates
1	191	spring 1972	48	fall 1972
2	168	spring 1972	48	fall 1973
3	156	spring 1973	46	fall 1973
4	156	winter 1974	46	spring 1974
5	22	spring 1977		
6	73	spring 1978		
7			17	spring 1979
8	54	fall & spring '81–'82	15	fall & spring '81–'82
9	38	fall & spring '82–'83	17	fall & spring '83–'84

had almost identical SAT scores, indicating we could consider these samples to be comparable in general ability.

A single investigator could not carry out the large number of interviews, so throughout the project I was assisted by my graduate students. Graduate students do not, however, stay forever. The long period of time meant that over the 13 years of the study (counting the final year of data gathering from the Uninstructed students), 24 different graduate students and staff persons participated in the interviews and interview interpretations. This feature of the study may be unique. I patterned my research group after the models I had come to know as a teaching and research assistant in the Botany Department at the University of Minnesota. Our research group worked with a common, explicit theoretical foundation, we held seminars regularly to discuss our research, our instructional development efforts in several projects in addition to the work reported here, and where we found difficulties in or new insights in our work. This teamwork was essential to maintain the momentum and consistency in methodologies as our work progressed.

The Invention of *Concept Mapping*

It is evident from Table 2 that we were accumulating hundreds of interview tapes. As we transcribed the tapes, we could observe that propositions used by students would usually improve in relevance, number, and quality, but it was still difficult to observe specifically how their cognitive structures were changing. Our research team considered various alternatives we might explore, and we also reviewed again

Ausubel's ideas regarding cognitive development. Three ideas from Ausubel's assimilation theory emerged as central to our thinking. First, Ausubel sees the development of new meanings as building on prior relevant concepts and propositions. Second, he sees cognitive structure as organised hierarchically, with more general, more inclusive concepts occupying higher levels in the hierarchy and more specific, less inclusive concepts subsumed under the more general concepts. Third, when meaningful learning occurs, relationships between concepts become more explicit, more precise, and better integrated with other concepts and propositions. The latter involves what Ausubel calls *progressive differentiation* of conceptual and propositional meanings, resulting in more precise and/or more elaborate ideas, and *integrative reconciliation,* or resolution of conflicting or ambiguous meanings or concepts and propositions. In our discussions, the idea developed to translate interview transcripts into a hierarchical structure of concepts and relationships between concepts, i.e., propositions. The ideas developed into the invention of a tool we now call the *concept map*.

We were somewhat surprised to find that we could rather easily transform the information in an interview transcript into a concept map. Figure 2 shows examples of concept maps we drew from interview transcripts for one above average Instructed student at the end of grades 2 and 12. Note that while new concepts such as "atom" are assimilated into her cognitive structure, she also has acquired some new misconceptions. This is characteristic of students who learn sometimes by rote and sometimes at relatively low levels of meaningful learning. Figures 3a and b show concept maps we drew from interview transcripts with one Uninstructed student at the end of grades 2 and 12. This latter student was obviously disposed to learn meaningfully rather than by rote, and he shows clear evidence of progressive differentiation and integrative reconciliation of his cognitive structure in this domain of knowledge. However, the mean quality of maps for Instructed students was substantially better than for Uninstructed students as will be shown below. We found that a 15–20 page interview transcript could be converted into a one page concept map without losing essential concept and propositional meanings expressed by the interviewee. This we soon realised was a very powerful knowledge representation tool, a tool that would change our research program from this point on.

In the history of science, there are many examples where the necessity to develop new tools to observe events or objects led to the development of new technologies. For our research program, the necessity to find a better way to represent children's conceptual understandings and to be able to observe explicit changes in the concept and propositional structures that construct those meanings led to the development of what has now become a powerful knowledge representation tool useful not only in education but in virtually every sector of human activity. It should be noted that although there were other knowledge or semantic structure representations prior to our development of concept maps, most of these are not hierarchically organised, do not contain explicit single concept labels in the "nodes," and usually do not have "linking words" between the concepts that are necessary to represent propositional meanings. Other forms of knowledge representation have been described by Jonassen, Beissner, and Yacci (1993), as well as by others.

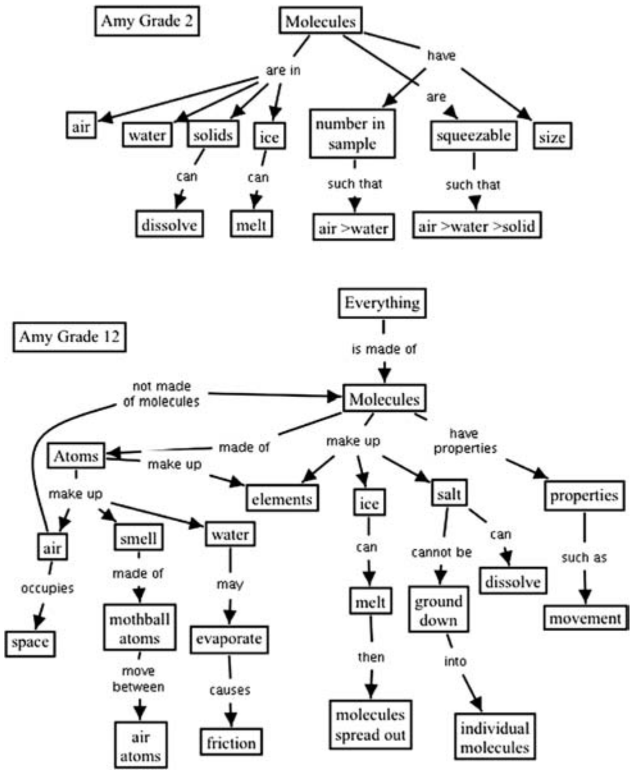
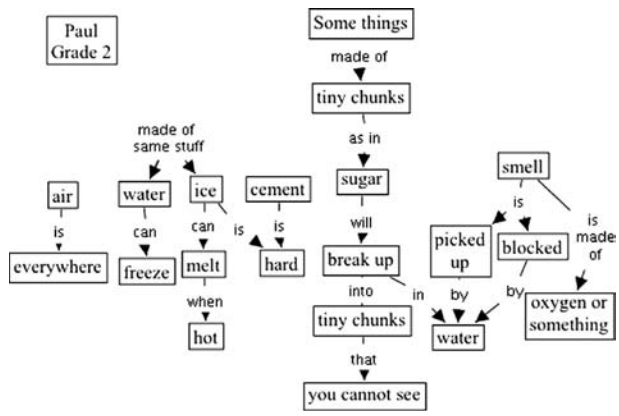
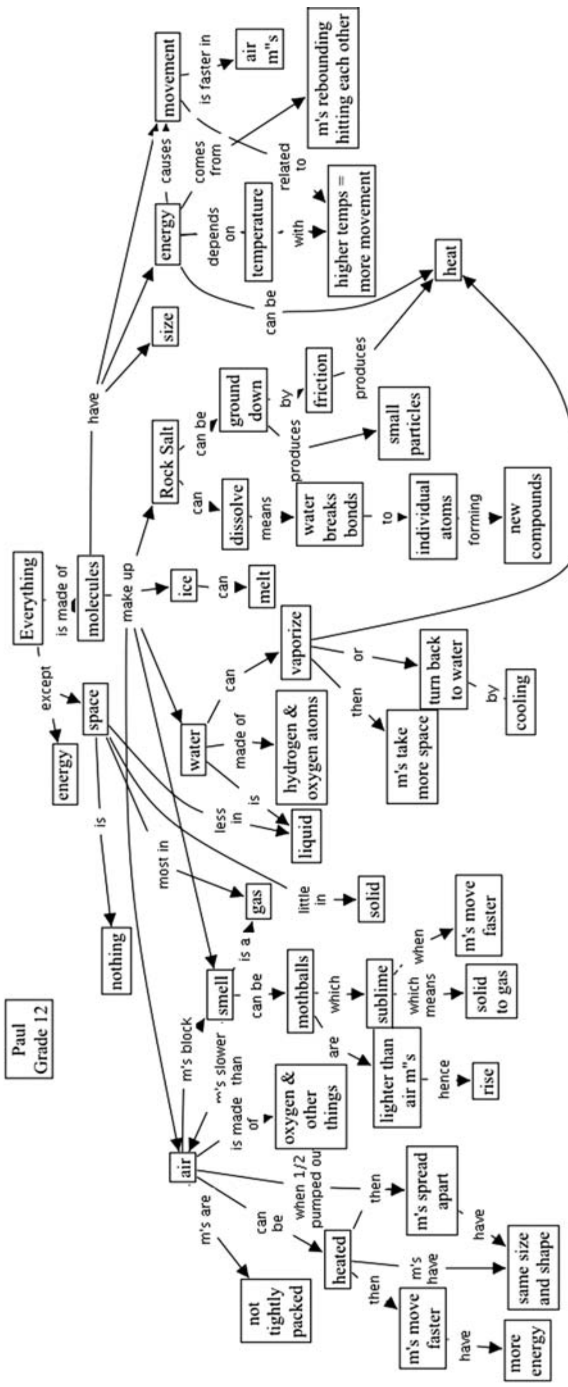


Figure 2: Two concept maps constructed from interviews with an above average Instructed student at the ends of grades 2 and 12.



(a)

Figure 3: Two concept maps constructed from interviews with an exceptionally good Uninstructed student at the ends of grades 2 (a), and 12 (b).



(b)

Figure 3: (Continued).

For our research project, the concept maps drawn from structured interviews became the primary tool we used to ascertain what learners know at any point in their educational experience. While it does take an hour or two for an experienced person to make a concept map from a 20–30 minute interview transcript, the precision and clarity of the learner's cognitive structure represented this way made it relatively easy to follow specific changes in the student's knowledge structures as she/he progressed through the grades. We also used concept maps made by our research staff to identify valid and invalid notions held by students.

In our study, the researchers constructed the concept maps from the transcripts of the interviews with the children. Later, and not in the study, we got students to construct maps directly, by giving them key terms which they had to arrange in meaningful patterns and then connect with lines that they labeled with the nature of the relation between the terms. When students are taught how to do this direct form of concept mapping, it is possible to use the concept maps they draw to observe the initial state of a learner's knowledge in a given domain, as well as to monitor changes in their cognitive structure. Edwards and Fraser (1983) have shown that students' concept maps can be as revealing of learners' cognitive structures as clinical interviews. We have found student concept maps to be good indicators of their knowledge when learners have sufficient skill in concept mapping and motivation to construct their own concept maps. We did not attempt to have students in our samples construct concept maps, since the training in the use of concept maps was not feasible. While our longitudinal study was in progress, we made little effort to encourage the use of concept maps, since this may have confounded our study results. A few teachers in Ithaca schools were interested in the use of concept maps, but most preferred to continue with their usual teaching practices.

It is important to note that these explicit changes were observed in different interviews done by different graduate students over the span of 12 years. We were careful to have graduate students draw concept maps without knowing whether the interviews were with Instructed or Uninstructed children. The consistency with which the same valid or faulty knowledge structures were shown in concept maps drawn by different researchers illustrates the robustness and reliability of the technique of representing children's understandings in the form of concept maps. Subsequently other investigators have also found concept maps to be reliable, valid indicators of conceptual understanding and changes in relevant concept and propositional structures over time (Kankkunen, 2001; Ruiz-Primo & Shavelson, 1996; Shavelson & Ruiz-Primo, 2000).

Major Findings of the Study

Using the concept maps drawn from interviews as the primary source of information, we extracted valid and invalid propositions or notions evidenced in the concept maps. It was clearly evident that Instructed children had fewer and fewer misconceptions as they progressed through school, when compared with Uninstructed students.

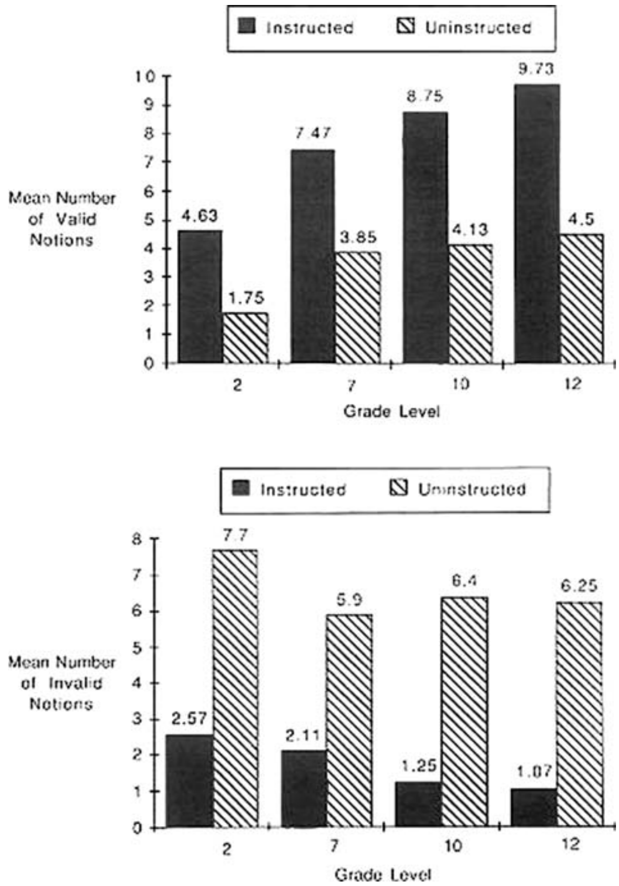


Figure 4: The number of valid and invalid notions held by Instructed and Uninstructed students in grades 2, 7, 10, and 12.

Conversely, the Instructed students had an increasing number of valid ideas or notions as they progressed through the grades. The results are shown in Figure 4. We see that by the end of grade 2 the Instructed students significantly outperformed the Uninstructed students in their understanding of energy and molecular kinetics ideas. When students begin the formal study of science in grade 7, both Instructed and Uninstructed students improve in their understanding of energy and molecular kinetics concepts, but a highly statistically significant ($p < .001$) superiority of Instructed students compared with Uninstructed students was observed, both for valid and invalid ideas. Moreover, the Instructed students showed steady improvement as they progressed through high school science courses, whereas improvements for Uninstructed students were small. This significant difference in performance over the years for the Instructed and Uninstructed groups led to a statistically significant interaction variance for years in school. Other statistical results have been reported elsewhere (Novak & Musonda, 1991). Clearly, the students who were helped to form basic science concepts in grades 1 and 2 had developed their cognitive structure (their *subsumers*, in Ausubelian terms) for energy and molecular kinetics ideas in a way that continued to facilitate their meaningful learning, further developing their understandings and reducing their misconceptions. Such remarkable results shout for replication, but to my knowledge, no one else has attempted a 12-year longitudinal study of children's science concept development.

It also was evident that 6 to 8 year-old students can acquire sufficient understanding of basic, highly abstract science concepts that can serve as a cognitive base for facilitating later learning. While this idea was widely disputed in 1965, by the time the study was completed this was no longer such a controversial idea, since other researchers had shown that we have grossly underestimated the cognitive capabilities of young children (Carey, 1985; Chi, 1983). Furthermore, the rigid adherence to the idea of limiting cognitive operational capacity of children was also falling by the wayside (see, for example, Flavell, 1985), although we still see in the science education community teachers and researchers referring to the inability of younger children to learn abstract concepts.

Another significant outcome of the study was to illustrate the power of carefully designed, technologically-mediated instruction. While admittedly we dealt with only a limited domain of science, we chose to focus upon the domain of molecular kinetics and energy transformations since this is a notoriously difficult area of instruction in science, especially at the elementary school level. Furthermore, an understanding of these ideas is essential to understanding almost all science phenomena.

Reflections

Ausubel and Piaget shared in common the recognition that children must construct for themselves the mental structures that would lead to proficient adult performance. However, while Piaget saw this as developing *generic* cognitive *operational* capacities, Ausubel spoke instead of the need to develop *specific,* highly organised, hierarchical conceptual and propositional structures in every domain where one seeks proficiency. Thus, with an Ausubelian framework, a child fails to conserve volume in various contexts because she lacks a *conceptual understanding* of the parameters that determine volume, and not some generic cognitive operational structure, as followers of Piaget would contend (Novak, 1977a, 1977b, 1982, 2002). The challenge we saw was to design instruction for young children that would assist them to develop the pertinent conceptual and propositional structures needed to understand and be able to use concepts such as the particulate nature of matter, energy, and energy transformations, among other basic science concepts.

The 1960s and 1970s was also a time when a new epistemology was emerging, catalysed by such works as Kuhn's (1962) *The Structure of Scientific Revolutions*, and Toulmin's (1972) *Human Understanding: The Collective Use and Evolution* *of Concepts*. This emerging realist or constructivist epistemology viewed the creation of new knowledge as a social, human endeavor, fraught with human successes and failures and constantly evolving. This contrasted with the "immutable truths" or "laws" that the positivist sought to derive from empirical studies "unfettered" by preconceived notions (Novak, 1977a, Chapter 2). Ausubel's assimilation theory could well serve as a foundation for constructivist epistemology, since it explained an individual's development of conceptual understanding in a way closely paralleling creation of knowledge in the sciences or any other discipline. Toulmin's description of the evolving nature of disciplinary concepts, with new ideas building upon and modifying existing concepts, could be seen as paralleling how an individual's conceptual understandings develop, as described by Ausubel (Novak, 1993). Today most members of the science education community embrace a constructivist epistemology, but this was certainly not the case during the early years of our longitudinal study.

There was in our data also support for the principal ideas in Ausubel's assimilation theory of cognitive development and general support for the value of cognitive over behavioral psychological theories. Here again the psychological landscape has changed quite dramatically, with virtually all educational psychologists moving to embrace *cognitive* theories of learning by the 1990s. In short, the cognitive learning and development ideas that were the foundation of our 12-year longitudinal study are now generally accepted, albeit much of this acceptance was based on hundreds of mostly short term "experiments" done by psychologists and educators, and many of these studies were driven by essentially positivistic epistemological assumptions.

Nevertheless, there remains considerable debate in science education circles on the cognitive limitations of young children, and therefore what science should be taught in early grades. In my view, the American Association for the Advancement of Science's *Benchmarks for Science Literacy* (1993) and *Atlas of Science Literacy* (2000), and the National Research Council's *National Science Education Standards* (1996), grossly underestimate the conceptual learning capability of younger children and unnecessarily and unwisely recommend postponement of instruction in basic energy and molecular kinetics ideas until the middle-school years. This precludes the early development of these fundamental concepts needed to understand almost any of the concepts in science, and relegates the early years largely to descriptive studies of biological and physical phenomena. Our 12-year study, and the research of others noted earlier, would argue against postponing instruction in molecular kinetics concepts, as well as other basic science concepts.

Vygotsky (1928/1978) introduced the idea of the "zone of proximal development" (ZPD), implying understandings a child has that can be built upon for further cognitive development. He anticipated Ausubel's idea that meaningful learning must begin with what the learner already knows. One of the values of concept maps is that when children construct their own concept maps for a question or problem in any domain, they reveal with considerable specificity what is their developmental potential for the topic of study. Thus we are provided with a clear view of "what the learner already knows" and we can design instruction to build upon this. We generally recommend that children build concept maps in small groups, since the exchange that occurs between children can often serve to correct faulty ideas and promote meaningful learning. In part this results from the fact that the cooperating students are at approximately the same level of understanding, much more so than teacher and student. Cooperative learning confers an advantage to students over the usual independent, competitive teaching approaches (Qin, Johnson, & Johnson, 1995).

Another use of concept maps is to provide maps made by experts to serve to "scaffold" learning of students (O'Donnell, Dansereau, & Hall, 2002). The idea of scaffolding learning goes back to early studies by Vygotsky where he described his research showing that language and the social exchange using language can significantly enhance children's cognitive development. Through proper use of language, adults can scaffold the learning of concepts by children. Although we were not aware of the scaffolding and ZPD ideas when we designed the audio-tutorial lessons, we were doing things congruent with these ideas. When we were designing our audio-tutorial lessons, we interviewed children to explore their thinking about a particular concept or problem and then designed experiences that would build on what they knew and would extend their ideas by providing hands-on experiences and appropriate scientific vocabulary to explain the events they were observing. Perhaps one of the reasons the relatively brief instructional experiences children had in audio-tutorial lessons in grades 1 and 2 had such a sustained impact on their later learning in sciences was that we were on the right track in working within children's ZPD and using activities and appropriate language to scaffold their learning.

Over the years that our longitudinal study was in progress, we became increasingly aware of the extent to which school learning programs lead most students into predominantly rote modes of learning. Some children, for reasons of their genetic make-up or early childhood experiences, resist the effect of school instructional and assessment practices that push students towards rote learning patterns. We have found that interviews and questionnaires can be used to assess individual's proclivities to learn by rote or meaningfully, with most people falling somewhere along a continuum from very rote learners to highly meaningful learners (Bretz, 1994; Edmondson & Novak, 1993). We wish now we had been more aware of the problem of commitment to rote learning and had made assessments of our students in grade 1 and subsequently of their preferred learning approach. It is likely that such data would have tracked well those students who progressed in their conceptual understandings over the 12 years, and those students who made little progress in their conceptual understanding. While it may be wishful thinking to consider that the audio-tutorial program would have shifted some children's patterns toward meaningful learning, it would have been wise to at least monitor this parameter. I would urge other researchers doing longitudinal studies to monitor their subject's disposition to learn with greater or lesser commitment to meaningful learning.

We have also found in our more recent research that it is useful to assess individuals' commitments to constructivist versus positivistic epistemological views (Chang, 1995; Edmondson & Novak, 1993). In general, we observe that learners who are more constructivist in their epistemological orientation are also more likely to employ meaningful learning strategies than learners who are more positivistic in their orientation. In recent years there has been a large increase in papers published in the *Journal of Research in Science Teaching* dealing with epistemological issues, including a recent paper by Sandoval and Morrison (2003) that deals with the relationship between learning approach and epistemological views held by students. I would urge researchers doing future longitudinal studies to include measures of learner's epistemological ideas, as well as their learning approach.

Audio-tutorial technology is now obsolete. We now have vastly more opportunity to facilitate learning in the sciences as well as in other fields using computer guided instructional strategies and excellent software available for concept mapping. I see great promise for instructional strategies that combine the use of "expert" concept maps to scaffold student and teacher learning using the Internet in conjunction with such software tools, inquiry activities and collaborative learning, as I have described elsewhere (Novak, 1998, 2003). These new tools and approaches should provide some very exciting research opportunities for future longitudinal studies that will show the potentials that young minds possess that are not being developed adequately in schools today.

Acknowledgement

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