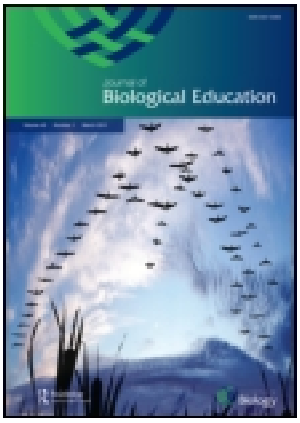

Journal of Biological Education
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rjbe20

Exploring students' cognitive structures in learning science: a review of relevant methods

Chin-Chung Tsai [a] & Chao-Ming Huang [b]

[a] Institute of Education and Center for Teacher Education, National Chiao Tung University , Hsinchu, Taiwan

[b] Department of Earth Sciences, National Taiwan Normal University , Taipei, Taiwan

Published online: 13 Dec 2010.

To cite this article: Chin-Chung Tsai & Chao-Ming Huang (2002) Exploring students' cognitive structures in learning science: a review of relevant methods, Journal of Biological Education, 36:4, 163-169, DOI: 10.1080/00219266.2002.9655827

To link to this article: http://dx.doi.org/10.1080/00219266.2002.9655827

Review

Exploring students' cognitive structures in learning science: a review of relevant methods

Chin-Chung Tsai[1] and Chao-Ming Huang[2]
Institute of Education and Center for Teacher Education, National Chiao Tung University, Hsinchu, Taiwan[1]; Department of Earth Sciences, National Taiwan Normal University, Taipei, Taiwan[2]

Understanding how people think and how people organise knowledge are always major concerns for educational researchers. Hence, educators have developed various ways of representing learners' 'cognitive structures'. This article provides a review of the use of five methods of representing cognitive structures – free word association, controlled word association, tree construction, concept map and flow map. Through comparing the types of analyses that are generated from these cognitive structure representation methods, this paper discusses the applications, as well as the limitations, among these methods.
Key words: Cognitive structure, Constructivism, Assessment, Concept map, Flow map.

Introduction

In the paradigm of constructivism, knowledge is actively constructed and personally situated. Hence, every individual may have different ways of organising knowledge. Exploring every individual's so-called 'cognitive structure' may become highly important when studying students' learning. Moreover, current practice in constructivism advocates the use of multiple methods of assessment for enhancing learning outcomes (Tsai, 1998a, 2000a, 2001a). Educators may include cognitive structure assessment as one of the multiple assessment modes (Shavelson *et al.*, 1990). In addition, an appropriate reflection and self-assessment of individual learning processes will facilitate conceptual change and development (Baird *et al.*, 1991). Through explicit analyses of the learner's cognitive structures, educators can not only understand the student's alternative conceptions (or misconceptions), but also help the student engage in metacognitive learning and thus enhance his or her learning outcomes.

Eylon and Linn (1988) have devised four categories of research in science learning:

- conceptual learning
- development
- differential
- problem solving

Conceptual learning focuses on the qualitative differences of concepts or the content and structure of knowledge students have acquired. Research about student 'misconceptions' or 'alternative conceptions' in recent decades is classified as this category. Misconceptions are those held by students that are at variance with scientific knowledge even after formal instruction (Yip, 1998). *Development* studies how students attain understandings throughout their lives. For example, students may develop different abilities in various life stages. A growing interest in this aspect may result in more attention to information processing capacity in relation to developmental stages during maturation. The category *differential* places an emphasis on individual differences in ability and aptitude. Moreover, research in this area probes the interaction of these differences with instruction. *Problem solving* explores the processes students employ to respond to scientific questions and open-ended, inquiry learning environments. In particular, problem solving research typically has investigated the differences in solving strategies between experts (e.g. scientists) and novices (e.g. students).

These four categories have some interesting relationships with findings from research on learners' cognitive structures. For example, it is known from problem solving research that experts can store and retrieve more information bits than novices. Former studies have also revealed that experts can store their information much more efficiently and retrieve it much faster than novices. This hypothetically occurs due to the well-elaborated cognitive structures of the experts (Chi *et al.*, 1985; de Jong & Ferguson-Hessler, 1986; Larkin *et al.*, 1980). That is, experts have well-developed or more integrated knowledge structures to help them solve problems. Furthermore, through exploration of cognitive structures, educators can better understand students' conceptual development in science and have identified their alternative conceptions or other non-scientific ways of explaining phenomena. This has had a practical benefit of improving science curricula and learning activities that take prior knowledge structures into account, and incorporate ways of helping students to meaningfully reorganise their understandings, to arrive at a more scientifically accurate view of natural phenomena. Educators can also explore how students of different abilities and aptitudes, and instruction with varied approaches, may have impacts on students' cognitive structures. If researchers have better ways of analysing students' cognitive structures, it is very likely that we can improve research on these four aspects of science learning.

In summary, having evidence of a learner's cognitive structure could be a fundamental step when we are looking toward understanding how students construct knowledge, which could be used to build up further knowledge during subsequent learning. In this article, we will discuss the significance of exploring cognitive structure and then review some methods and their forms of representation with a critical comparative analysis of their advantages. Some suggestions toward employing these methods in further research in science education will also be proposed.

The significance of exploring cognitive structure

A cognitive structure is a hypothetical construct representing the relationships of concepts in a learner's long-term memory (Shavelson, 1974). Some researchers may use different terms to describe cognitive structure, such as, for example, *structural knowledge* (Jonassen *et al.*, 1993; Diekhoff & Diekhoff, 1982). As they ascertain, structural knowledge shows the interrelationships between ideas in a knowledge domain. Besides, structural knowledge is related to information processing for organised networks of ideas stored in semantic or long-term memory. In summary, a cognitive structure contains learners' existing experiences and knowledge that will dominate their reconstruction and information processing of the incoming stimuli (Tsai, 2001b).

Educational research has repeatedly revealed that many students put great effort in memorising, but only a few can apply disciplinary knowledge to their daily life or decision making (Tsai, 1998b, 1998c). Many students' cognitive structures are a collection of isolated bits of information. It is plausible that poor cognitive structure will result in poor information processing or inefficient acquisition of new knowledge, and ultimately this will influence one's academic achievement and ability to apply knowledge to daily situations.

To state it more specifically, what benefits can educators obtain from exploring one's cognitive structure? We can briefly answer this question from three perspectives, including prior knowledge, assessment and metacognition. By means of explicit representation of learners' cognitive structures elicited before instruction, educators can obtain their prior knowledge (Ausubel *et al.*, 1978) or alternative conceptions (Wandersee *et al.*, 1994). Even though there is a plethora of terms concerned with so-called prior knowledge in science (e.g. intuitive science – Preece, 1984; naive theory – White & Gunstone, 1989), educators still have some convergent views about prior knowledge. Prior knowledge at least has the following four attributes:

- It is mainly based on students' life experience;
- Students' prior knowledge sometimes is different from formal knowledge used by scientists or teachers;
- It is resistant to change, or it is tenacious, even through conventional formal instruction;
- Prior knowledge will influence learning processes or conceptual development.

The exploration of cognitive structure can help teachers know what their students have already assembled in memory and to what extent it is compatible with accepted norms in a disciplinary field or incongruent. Knowing one's prior knowledge can guide teachers to design appropriate teaching strategies, assist students to connect past experiences and new incoming information, and consequently enhance meaningful learning. Therefore, knowing a student's alternative conceptions can not only help teachers improve teaching strategies but also help students work on conceptual change (Posner *et al.*, 1982).

Current practice in education encourages the use of multiple ways to assess students' performance. Here, we propose that the measurement of cognitive structure can be one of the better indicators in assessing what learners know rather than traditional paper-and-pencil tests. In other words, through probing students' cognitive structures, educators can understand what students learn and how their knowledge may change during the learning processes. The assessment of students' cognitive structures can partially replace the traditional paper-and-pencil test. As Shavelson *et al.* (1990) mentioned, assessment has to provide two valid indicators – cognitive fidelity and process relevance. *Cognitive fidelity* indicates the congruence of conceptual understanding. Since it concerns the major organising principles that guide knowledge construction, it will influence students' attention, judgement, plans and goal for learning. *Process relevance* assesses how well students apply learned concepts or skills to their daily life. The assessment of cognitive structure may offer more information about these two indicators than traditional paper-and-pencil tests. For instance, through analysing student concepts and their relationships shown in cognitive structures, the indicator of cognitive fidelity can be revealed. Also, students' cognitive structures may more possibly display how they relate learned concepts to life experiences, as cognitive structures can allow students more flexibility in expressing their ideas. Investigating students' cognitive structures is not only a practical assessment method, but also offers the opportunity for teachers to examine their teaching strategies. By monitoring students' cognitive structure development combined with the teacher's self-reflection of his or her own teaching strategies, the teacher can lead to more relevant and informed design of learning experiences that complement the cognitive development of the learners.

As a result, numerous biology educators and teachers have tried to use the cognitive structure exploration (such as the methods of concept mapping or word association) in practice. For example, Marbach-Ad (2001) used concept maps (and some interviews) to probe the comprehension of genetic concepts among a group of ninth graders (14- and 15-year-olds), 12th graders (17- and 18-year-olds) and trainee teachers, and found that genetic instruction in ninth and 12th grade and in college needed improvement. Bahar *et al.* (1999) used word association tests to explore 280 first-year biology (college) students' cognitive structures about genetics. The words such as 'gene', 'cell division' and 'chromosome' were provided to act as stimuli for the tests. The study revealed that the students generated many ideas related to given key words, but they did not see the overall picture as a network of relevant ideas. Tsai and Huang (2001) documented a group of fifth graders' (11-year-olds) cognitive structure development about the topic of biological reproduction, and found that the rich connections between concepts and higher-order cognitive operations might facilitate the maturation of connected knowledge in memory. They suggested that biology teachers needed to encourage students to use higher level information processing during biology instruction.

Finally, an analysis of one's own cognitive structures, for example when a student is allowed to examine a map or other representation of her or his knowledge recall, can enhance metacognition and more reflective analysis of how to improve one's own learning (Novak, 1990; Tsai, 2001b). The student can retrospectively reflect on his or her specific concepts or alternative conceptions and compare existing structures in memory with previous ones at an earlier time, or in relation to the knowledge organisation of others. Such reflection can facilitate individual critical reflection during learning how to learn, and moreover enhance conceptual development (Baird *et al.*, 1991). In addition, presenting and discussing students' cognitive structures can allow students to scrutinise their thinking (Diekhoff & Diekhoff, 1982), and then promote higher order learning outcomes.

In conclusion, revealing students' cognitive structures can have benefits to both the teacher, in designing learning, and to the learner in enhancing skills that promote more self-directed learning. For teachers, revealing students' cognitive structure can assist teachers to probe students' prior knowledge and then develop more appropriate instructional strategies to enhance learning outcomes. On the other hand, probing students' cognitive structures can also help teachers to assess what students have learned during the teaching processes. As a metacognitive tool, revealing cognitive structures can facilitate conceptual development and conceptual change.

A review of different methods

In recent decades, researchers have proposed several ways of representing people's cognitive structures. Major issues in representing people's cognitive structures include how to use quantitative terms for a valid description and how to display the cognitive structure information through visual formats.

There are five common methods of eliciting and representing cognitive structures – free word association, controlled word association, tree construction, concept map and flow map. The following is a brief overview of the procedures typically used for these five methods:

1. Free word association

The administrators or experts offer a main concept and ask a respondent to write down all relevant concepts and as many as possible on a plain paper without time limit. In this method, the respondent is asked to repeat the same word association task after completing the previous test, a total of 10 times. Figure 1 shows a sample of a free word association in which the main concept is photosynthesis. In this figure, the respondent is asked to write down related concepts freely. After completing the whole test, researchers count the frequency of respondent-recalled concepts from the ten free word association sheets. According to the semantic similarity, researchers determine the frequencies of a pair of concepts and then use a matrix to calculate their distance values and to display the connections among concepts.

	Photosynthesis
1	Sun light
2	Plants
3	Carbon dioxide
4	energy
5	chlorophyl

Figure 1 *Free word association.*

2. Controlled word association

The test administrators offer a main concept and limited space for a respondent to write down relevant concepts. This means that the respondents have to decide which concept is a very important one that is related to the main concept. This eliciting process has to be completed within one minute per main concept. Figure 2 shows a sample of controlled word association with the same main concept of photosynthesis. Clearly, the most important difference between the free word association and controlled word association is their scoring method. In the controlled word association, the respondent has to take the concepts' importance into account and arrange their order among elicited concepts in accordance with his/her cognitive structures. Controlled word association also needs complex matrix calculation (for details, see Jonassen *et al.*, 1993).

Rank	Photosynthesis	Score
1	Plants	5
2	Sun light	4
3	Carbon dioxide	3
4	chlorophyl	2
5	energy	1

Figure 2 *Controlled word association.*

3. Tree construction

Tree construction is the archetype of concept mapping. In the tree construction method, the respondent will write down a relevant concept that has some relation with the former one from a given concept list. This technique can show how close the relationship is among pairs of concepts and also their hierarchical attributes as obtained with a concept map. Figure 3 shows a sample of a cognitive structure that is derived from a tree construction. To portray the interrelationships of the ideas obtained from the tree construction, a complex matrix calculation is also necessary (for details see Jonassen *et al.*, 1993).

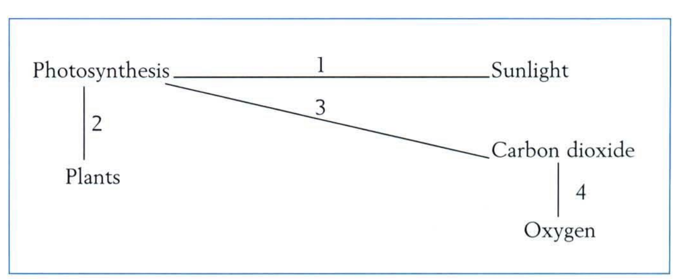

Figure 3 *Tree construction.*

4. Concept map

The unit of a concept map is a *proposition*. Two concepts and one linkage constitute one proposition. A concept map not only shows the relationships between concepts, but also displays the hierarchy of cognitive structures, when the student properly follows the rule of subsumptive organisation of ideas while constructing the maps. Figure 4 shows a sample of a concept map constructed by a fifth grader (11-year-old). Concept map construction requires students to integrate and present their concepts hierarchically; therefore the concept map could be a decorated or elaborated one. This may not show the respondent's authentic cognitive structure, since there is some constraint imposed by the administrator in recommending at least that the information should be organised from most inclusive to least inclusive. Concept maps have been used more for instructional than assessment purposes (Ruiz-Primo & Shavelson, 1996).

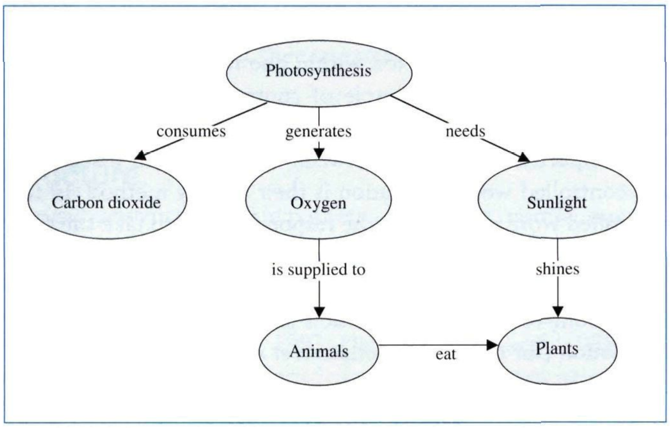

Figure 4 *A concept map about photosynthesis by a fifth grader.*

5. Flow map

The flow map method is a relatively new method of representing learners' cognitive structures. This method will therefore be described in more detail. The goal of employing a flow map method is to capture both the sequential and network features of people's thought in a non-directive way. Interviews are used to obtain a record of student narratives to be analysed as evidence of the student's cognitive structures. Since this part of the interview needs to be conducted in a non-directive way to help the student express what he or she knows with minimum bias by the interviewer, the interview questions are kept as simple as possible. For example, in the case of photosynthesis, the interview questions could be:

(1) Please tell me what the main parts of the photosynthesis process are.
(2) Can you tell me more about the parts you have identified?
(3) Can you tell me the relationships among some of the ideas you have already told me?

The responses to these questions are tape-recorded, and then transcribed into the format of a flow map. Figure 5 demonstrates a sample flow map that came from the same respondent in Figure 4. Basically, the flow map is constructed by entering the statements (equivalent to a clause or sentence) in sequence as they were mentioned by the student. The sequence of discourse is examined and recurrent ideas represented by recurring word elements in each statement (representing a connecting node to prior thought) are linked by connecting arrows. The linear or serial arrows show the direct flow of student narrative, while recurrent linkages show revisited ideas among the statements displayed in the flow map. For example, the student's narrative mapped in Figure 5 shows a sequential pattern beginning with the conditions of photosynthesis and then its products and functions. Moreover, recurrent arrows are inserted that link revisited ideas to the earliest step where the related idea (i.e. revisited idea) first occurred. Statement five, for example, 'The oxygen produced can help people breathe' includes one major revisited idea 'oxygen'. Therefore, statement five has one recurrent arrow drawn back to statement four (i.e. the earliest step containing a statement about oxygen; for further details about the flow map method, see Anderson & Demetrius, 1993; Anderson, Randle & Covotsos, 2001; Bischoff & Anderson, 1998, 2001; Tsai, 1998b, 2000b, 2001b; Tsai & Huang, 2001). A flow map representation has a merit of exhibiting both the sequential pattern of recall and also evidence of an underlying interconnected texture of ideas in cognitive structures. Researchers can also estimate the respondent's information retrieval rate by entering time markers on the flow map at regular intervals as the narrative unfolds (shown in Figure 5). It should be noted that the time is measured after subtracting the interval of time where the interviewer is speaking. That is, only the time elapsed during the respondent's narrative is included.

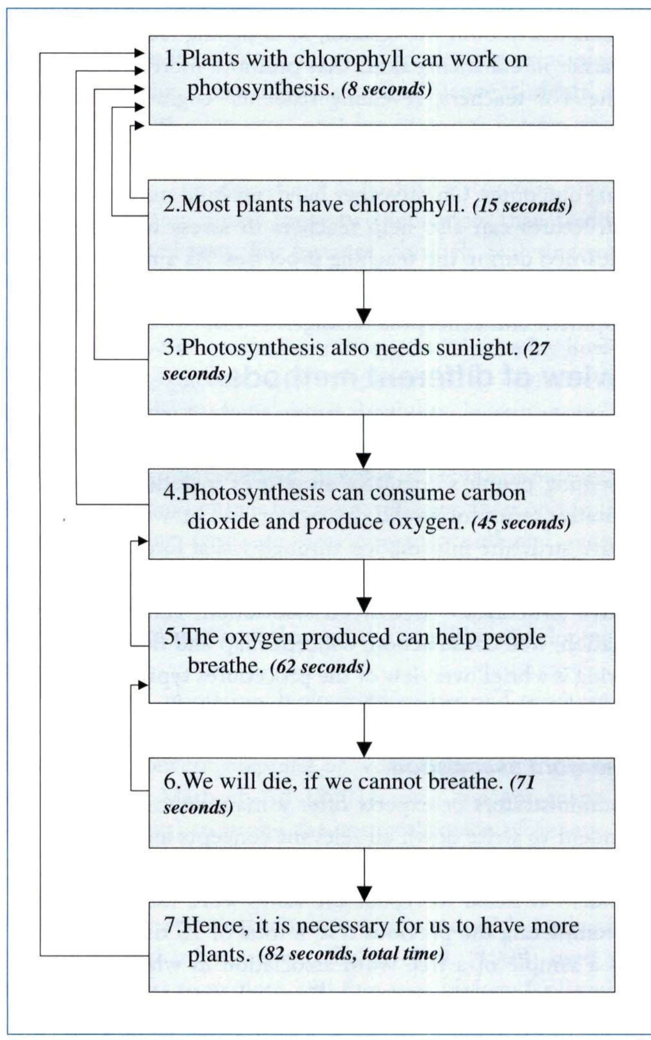

Figure 5 *A flow map about photosynthesis by a fifth grader.*

A comparison of methods

There are three major aspects in describing cognitive structures, including the concepts or ideas contained, the connections among concepts and the information processing skills. Among the criterial variables used to evaluate elicited concepts are their extent and correctness. Extent indicates the quantity of elicited concepts within an individual's cognitive structure, while the correctness deals with the accuracy among concepts expressed by the respondent. In addition to the extent and correctness, the connection among concepts in cognitive structures is another important issue. Connection indicates the degree of integration among concepts. Availability – how facile the respondent is in retrieving information within a given task context – together with analyses of information processing strategies revealed during information recall can be used to gain data about information processing skills. Some major aspects and variables of cognitive structure relevant to the theme of this paper are listed in Table 1.

Table 1 Aspects and variables of cognitive structures.

Aspects	Variables
Concepts	Extent, Correctness
Connection	Integration
Information processing skills	Availability, Analyses of information processing strategies

As a result, these three aspects include five different variables, which are described as follows:

1. **Extent** – the number of ideas contained in one's cognitive structures.
2. **Correctness** – the number of alternative conceptions shown in cognitive structures, or the number of correct conceptions.
3. **Integration** – the connection of cognitive structures. A well-organised structure is similar to a well-structured database. Users can find the information efficiently.
4. **Availability** – the availability of cognitive structures can be represented by information retrieval rate. That is, the time required to mobilise and retrieve ideas can show the availability in cognitive structures (Tsai, 1998b, 2001b).
5. **Analyses of information processing strategies** – by means of content analyses of cognitive structures, researchers can investigate individuals' information processing operations, such as the use of defining, describing, inferring or explaining (Tsai, 1999). For example, the first statement recalled by the student in Figure 5 that 'Plants with chlorophyll can work on photosynthesis' can be categorised as the use of 'describing' information processing operation. Through categorising elicited concepts and their relationships, researchers can explore the information processing strategies among respondents.

Table 2 shows some differences among five methods of representing cognitive structure in relation to these five variables. According to Table 2, it seems that the methods of concept map and flow map can offer relatively more information in analysing the variables about cognitive structure than the other three. The information elicited from free word association, controlled word association and tree construction may not clearly show the correctness of student cognitive structures. For example, if a student writes 'oxygen' as a relevant concept to 'photosynthesis' in the free word association task, researchers still can not judge if he or she has correct knowledge connection between these two concepts. The methods of free word association, controlled word association and tree construction also require complex mathematical calculation when showing the integration among concepts. Besides, repeatedly doing the same word association tasks may lead the respondent to become bored and this will endanger the validity of the knowledge structure task.

There is an important difference between concept maps and flow maps that should be emphasised, that is, 'availability'. In this context, the availability of cognitive structures is represented by the information retrieval rate. The concept map task often asks students to construct as many of their own concepts as possible, perhaps within fixed interval. Educators can only obtain the final result of the concept map and they may not catch the time consumed for mental information processing by the learners. By means of flow map methods, researchers can obtain a coefficient of availability by taking the quotient of the number of utterances recalled divided by the total time. This is also a form of retrieval index. By comparing retrieval rates among individuals, especially in relation to differing demands imposed by varying cognitive tasks, researchers can acquire more information about the dynamic nature of cognitive structure development (Anderson & Demetrius, 1993; Tsai, 1998b).

The analysis of information processing strategies is another important difference among these five methods. Exploring one's information processing strategies may help researchers monitor a learner's progress during cognitive structure development or trace the processes of learning as they unfold in a specified period of time. When educators have a tool to analyse the dynamic processes and variety of cognitive operations that occur during knowledge development, they may have more potent diagnostic information to solve problems of students' learning and to offer effective teaching strategies to promote more efficient learning outcomes. It appears that among the analytical procedures reviewed here, only the flow map method attains these purposes well.

By comparing Figure 4 with Figure 5, which were both obtained from the same respondent, it seems that the respondent was able to express more concepts through the method of flow map analysis compared to concept map production. It may not be very easy for elementary school students to integrate their ideas or daily experiences into a hierarchical and integrated framework of concepts, as is required by a concept map method. Thus, narrative analysis as used in the flow map technique may be more effective in tapping the extent and organisation of knowledge among respondents who have limited lexical capacity. Researchers have to take the age of the respondent into

Table 2 The variables of cognitive structures and the methods of probing cognitive structures.

	Free word association	*Controlled word association*	*Tree construction*	*Concept map*	*Flow map*
Extent	**	*	**	**	**
Correctness				**	**
Integration	*	*	*	**	**
Availability	*	*			**
Information processing strategy analyses					**

** = Definitely, * = Possibly

consideration when exploring a learner's cognitive structure.

The use of flow maps may gain some support from neurobiology research. Recently, evidence from neurobiology has been mobilised to enhance theory building and to provide a scientific framework for understanding the manifold functions of cognitive structure and processing of information flow in the human brain (Anderson, 1997; Baddeley, 1992; Wilson *et al.*, 1993). This emergent field, combining data from the neurosciences and cognitive psychology, is generally known as neurocognitive science and has begun to explain knowledge structures, metacognitive processes and problem solving, and the role of emotion and motivation in learning in terms of fundamental neural structures and their plasticity (Anderson, 1991, 1992). Knowledge structures may be correlated with neural schema or networks of connected neuronal elements, but probably of a distributed nature. That is, a unit of knowledge is not localisable to a particular point in the cerebral cortex but is widely encoded within elaborate, extended neural assemblages. Moreover, memory or the recall of experience is almost certainly not a process of encoding and a part-for-part readout as from a tape recording. The best evidence is that memory is reconstructed from component parts of knowledge, assembled in relation to certain organising principles characteristic of the learner's history, and the demands of the task at the time of recall. Thus, knowledge structures are viewed as organised but also malleable and adaptable depending on the stream of ongoing experience. Hence, research strategies for representation of knowledge structures should take into consideration the dynamic qualities of reconstructive memory in addition to the more stable organising principles that give it coherence and a degree of predictability. In light of current neuroscience perspective, the flow map method may be a better way of representing cognitive structures among those reviewed in this paper, as it can capture more about the dynamic nature of knowledge structure without imposing predetermined organisation such as hierarchical.

Conclusion

Each of the five methods reviewed in this paper has its own advantages and limitations. For example, free word association, controlled word association and tree construction require researchers to conduct more complex matrix calculations than the remaining methods. The calculations are sufficiently complex that sophisticated computer software is required. The most powerful merit of concept maps is that researchers can obtain visual displays of a student's cognitive structures generated directly by the student who draws the maps. However, researchers may need to spend some considerable time on training students to draw their own concept maps, and in the process can bias the product produced by the respondent. While flow maps can offer richer and somewhat more powerful indicators for representing cognitive structure, the method also has its own limitations. The raw data of flow maps are obtained from respondents' interview narratives, and thus while less prone to administrative bias, the task of transcribing and coding the flow map can be time consuming. The flow map technique does not require extensive time to train students in advance; however, researchers have to draw these flow maps individual by individual. This drawing processing may be a time-demanding task.

In conclusion, by probing students' cognitive structures, teachers can design more appropriate teaching strategies that will enhance students' learning outcomes. Furthermore, the teacher can assess students' learning outcomes through the exploration of their cognitive structures. Exposition of students' cognitive structures for their own reflective analysis, can also help them understand the weakness of their knowledge structures and to revise their understandings through additional more organised knowledge acquisition. A careful reflection and retrospection about one's own knowledge structure, or an analytical comparison with others' cognitive structures, can help learners construct more integrated and scientifically sound knowledge structures for further applications. The methods reviewed in this paper may provide some directions for teachers who are interested in exploring student cognitive structures and possibly adapting the methods to improve their professional practice, or to begin a classroom-based research program.

Acknowledgements

This research work was supported, in part, by funds from National Science Council, Taiwan, under grants NSC 89-2511-S-009-027, NSC 90-2511-S-009-001. The authors also express their gratitude to Professor O Roger Anderson at Teachers College, Columbia University, for his helpful comments on an early version of this paper.

References

Anderson O R (1991) Neurocognitive models of information processing and knowledge acquisition. *Progress in Sensory Physiology*, **12**, 115 – 192.

Anderson O R (1992) Some interrelationships between constructivist models of learning and current neurobiological theory, with implications for science education. *Journal of Research in Science Teaching*, **29**, 1037 – 1058.

Anderson O R (1997) A neurocognitive perspective on current learning theory and science instructional strategies. *Science Education*, **81**, 67 – 89.

Anderson O R & Demetrius O J (1993) A flow-map method of representing cognitive structure based on respondents' narrative using science content. *Journal of Research in Science Teaching*, **30**, 953 – 969.

Anderson O R, Randle D & Covotsos T (2001) The role of ideational networks in laboratory inquiry learning and knowledge of evolution among seventh grade students. *Science Education*, **85**, 410 – 425.

Ausubel D P, Novak J D & Hanesian H (1978) *Educational Psychology: A cognitive view.* New York, USA: Holt, Rinehart & Winston.

Baddeley A (1992) Working memory. *Science*, **235**, 556 – 559.

Bahar M, Johnstone A H & Sutcliffe R G (1999) Investigation of students' cognitive structure in elementary genetics through word association tests. *Journal of Biological Education*, **33**, 134 – 141.

Baird J R, Fensham P J, Gunstone R F & White R F (1991) The importance of reflection in improving science teaching and learning. *Journal of Research in Science Teaching*, **28**, 163 – 182.

Bischoff P J & Anderson O R (1998) A case study analysis of the development of knowledge schema, ideational networks and higher cognitive operations among high school students who studied ecology. *School Science and Mathematics*, **98**, 228 – 237.

Bischoff P J & Anderson O R (2001) Development of knowledge frameworks and higher order cognitive operations among secondary school students who studied a unit on ecology. *Journal of Biological Education*, **35**, 81 – 88.

Chi M T H, Feltovich P J & Glaser R (1985) Categorization and representation of physics problem by expert and novices. *Cognitive Science*, **5**, 121 – 152.

De Jong T & Ferguson-Hessler M G M (1986) Cognitive structures of good and poor novice problem solvers in physics. *Journal of Educational Psychology*, **78**, 279 – 288.

Diekhoff G M & Diekhoff K B (1982) Cognitive maps as a tool in communicating structural knowledge. *Educational Technology*, **22**, 28 – 30.

Eylon B & Linn M C (1988) Learning and instruction: An examination

of four research perspectives in science education. *Review of Educational Research*, **58,** 251 – 301.
Jonassen D H, Beissner K & Yacci M (1993) *Structural knowledge: Techniques for representing, conveying and acquiring structural knowledge.* New Jersey, USA: Lawrence Erlbaum Associates, Inc.
Larkin J, McDermott J, Simon D P & Simon H A (1980) Expert and novice performance in solving physics problems. *Science,* **208,** 1335 – 1342.
Marbach-Ad G (2001) Attempting to break the code in student comprehension of genetic concepts. *Journal of Biological Education,* **35,** 183 – 189.
Novak J D (1990) Concept mapping: A useful tool for science education. *Journal of Research in Science Teaching,* **27**, 937 – 949.
Posner G J, Strike K A, Hewson P W & Gertzog W A (1982) Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, **66**, 211 – 227.
Preece P F W (1984) Intuitive science: Learned or triggered? *European Journal of Science Education*, **6**, 7 – 10.
Ruiz-Primo M A & Shavelson R J (1996) Problems and issues in the use of concept maps in science assessment. *Journal of Research in Science Teaching,* **33**, 569 – 600.
Shavelson R J (1974) Methods for examining representations of a subject-matter structure in a student's memory. *Journal of Research in Science Teaching,* **11**, 231 – 249.
Shavelson R J, Carey N B & Webb N M (1990) Indicators of science achievement: options for a powerful policy instrument. *Phi Delta Kappan,* **71,** 692 – 697.
Tsai C-C (1998a) Science learning and constructivism. *Curriculum and Teaching,* **13**, 31 – 52.
Tsai C-C (1998b) An analysis of Taiwanese eighth graders' science achievement, scientific epistemological beliefs and cognitive structure outcomes after learning basic atomic theory. *International Journal of Science Education*, **20**, 413 – 425.
Tsai C-C (1998c) An analysis of scientific epistemological beliefs and learning orientations of Taiwanese eighth graders. *Science Education* **82**, 473 – 489.
Tsai C-C (1999) Content analysis of Taiwanese 14 year olds' information processing operations shown in cognitive structures following physics instruction, with relation to science attainment and scientific epistemological beliefs. *Research in Science & Technological Education,* **17**, 125 – 138.
Tsai C-C (2000a) Relationships between student scientific epistemological beliefs and perceptions of constructivist learning environments. *Educational Research*, **42**, 193 – 205.
Tsai C-C (2000b) The effects of STS-oriented instruction on female tenth graders' cognitive structure outcomes and the role of student scientific epistemological beliefs. *International Journal of Science Education*, **22**, 1099 – 1115.
Tsai C-C (2001a) The interpretation construction design model for teaching science and its applications to Internet-based instruction in Taiwan. *International Journal of Educational Development*, **21**, 401 – 415.
Tsai C-C (2001b) Probing students' cognitive structures in science: The use of a flow map method coupled with a meta-listening technique. *Studies in Educational Evaluation*, **27**, 257 – 268.
Tsai C-C & Huang C-M (2001) Development of cognitive structures and information processing strategies of elementary school students learning about biological reproduction. *Journal of Biological Education,* **36**, 21 – 26.
Wandersee J H, Mintzes J J & Novak J D (1994) Research on alternative conceptions in science. In Gabel D L (Ed.), *Handbook of Research on Science Teaching,* pp. 177 – 210. New York, USA: Macmillan.
White R T & Gunstone R F (1989) Metalearning and conceptual change. *International Journal of Science Education*, **11**, 577 – 586.
Wilson F A, O'Scalaidhe S & Goldman-Rakic P (1993) Dissociation of object and spatial processing domains in primate cortex. *Science,* **260,** 1955 – 1958.
Yip D Y (1998) Children's misconceptions on reproduction and implications for teaching. *Journal of Biological Education*, **33**, 21 – 26.

Chin-Chung Tsai is a Professor at Institute of Education and Center for Teacher Education, National Chiao Tung University, 1001 Ta Hsueh Rd., Hsinchu 300, Taiwan. Tel. +886 3 5731671; Fax. +886 3 5738083; Email: cctsai@cc.nctu.edu.tw. Chao-Ming Huang is a doctoral student at Department of Earth Sciences, National Taiwan Normal University, Taipei, Taiwan.