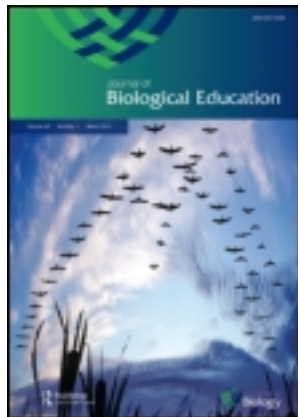


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Development of cognitive structures and information processing strategies of elementary school students learning about biological reproduction

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The purpose of this study was to explore 28 Taiwanese fifth graders' development of knowledge on biological reproduction. The students received three weeks of instruction about biological reproduction and were interviewed to determine their cognitive structures. The interviews were conducted three times, at weekly intervals throughout the instruction, and an additional interview was conducted two months after the instruction. The interview data were analysed through a flow map method to show cognitive structure, and the students' information processing strategies, derived from an analysis of the flow map data, were also explored. The results suggest that there are three stages of cognitive structure development. In the first stage, categorised as 'knowledge development', both the extent of knowledge and the richness of networking of ideas increase. In the second stage, categorised as 'knowledge extension', only the amount of knowledge continues to increase. In the final stage, called 'knowledge refinement', the amount of knowledge recalled decreases, while the richness in networking of ideas remains stable. At the same time, the use of higher-order information processing modes (e.g., narrative containing statements inferring and explaining) increases dramatically. This implies that the rich connections between concepts and the use of higher-order information processing strategies may facilitate maturation of connected knowledge in memory.

Key words: Cognitive structure, Biological reproduction, Flow map, Taiwan.

Introduction

Understanding how students acquire knowledge is always an important issue for science education researchers. Educators and cognitive scientists have tried to represent acquired knowledge in terms of 'cognitive structures'. A cognitive structure is a hypothetical construction showing the relationships between concepts in a learner's long-term memory (Shavelson, 1974). Over the past two or three decades, many science educators have explored aspects of student cognitive structures using a variety of methods (e.g., Preece, 1976; West and Pines, 1985; Bahar *et al.*, 1999). However, many early studies on cognitive structures have certain limitations. First, they focused largely on more mature students (high school or college students). Secondly, many of them did not document the development of student cognitive structures over time. Hence, most of these former studies did not provide information about how students' knowledge interacted with instruction as it unfolded, nor how students developed conceptual knowledge during instruction.

To contribute more broadly to our understanding of how students develop knowledge networks, the present study explored a group of elementary school pupils' conceptual development during short-term instruction on biological reproduction. Their knowledge recall using interview methods was examined to determine how the instruction may have influenced their ideational development of biological reproduction, and knowledge networking in particular. This study also investigated student information processing strategies based on content analyses of their recall narratives. This may provide a deeper understanding about the nature of student knowledge construction during meaningful learning, as typically occurs in the classroom.

Clearly, research of this kind on cognitive structures is consistent with current constructivist theory as applied to science instruction (Bodner, 1986; Anderson, 1992). Constructivist theory asserts that knowledge is actively constructed by the learner and is not simply recorded in memory. Therefore, every learner within the same learning environment is likely to develop dif-

ferent cognitive structures and varied ways of organising scientific information, even though the information presented and the conditions of learning may superficially seem identical. Furthermore, research on cognitive structures is consistent with schemata theory (e.g., Howard, 1988). The research reported here could be viewed as an investigation into how new experiences influence the reconstruction of existing schemata.

To summarise, this study explored how a group of elementary school pupils developed organised representations of knowledge about biological reproduction and how their information processing strategies changed during the course of biological instruction.

Method

Subjects

A fifth grade class of 32 pupils (11 years old) in Taiwan participated in this study. However, four students did not finish all of the data collection, therefore their data were excluded from final analyses. The final sample included 14 boys and 14 girls. Their teacher is an experienced male teacher with more than 10 years of teaching experience.

Description of lessons taught

According to the National Standards of Elementary Science Education in Taiwan, the instructional unit on biological reproduction for fifth graders should take about nine 40 minute class periods. Consequently, the students in this study received three periods of relevant instruction, which were arranged into three successive weeks (three periods per week). The regular teacher was the instructor for these classes. The first two weeks covered different methods of flowering plant reproduction. The first week largely focused on the use of seeds for vegetative reproduction. The second week mainly covered the use of other parts of plants for reproduction (for example, stems, roots). In the final week, different methods of fauna reproduction, including viviparity, oviparity, and ovoviviparity were introduced. In these three weeks, the students also had an opportunity to plant some seeds and record their growth.

Flow map method

Interviews were used to obtain a record of student narratives to be analysed using flow map methods as evidence of the student's cognitive structures. Since this part of the interview needed 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 were kept as simple as possible, e.g.:

- Please tell me what are the main ideas or ways of biological reproduction.
- Could you tell me more about the ideas you have mentioned?
- Could you tell me the relationships between the ideas you have already told me about?

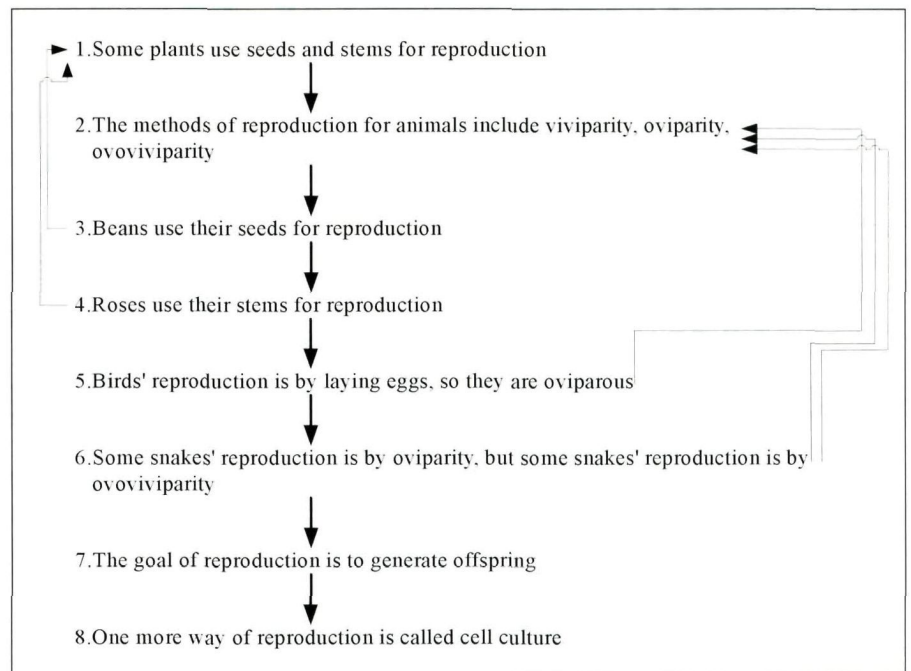


Figure 1 John's (pseudonym) flow map about biological reproduction (obtained from the third interview).

The responses to these questions were tape-recorded, and then transcribed into the format of a flow map (Anderson and Demetrius, 1993). Figure 1 shows a student's flow map about biological reproduction. The flow map is constructed by entering the statements (equivalent to a clause or sentence) in the sequence they were uttered by the student. The sequence of discourse is examined and recurrent ideas (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. (It should be noted that not all of the revisited ideas were elicited by the third interview question presented previously. Students' narratives contained many revisited ideas probed by other interview questions.) For example, the student's narrative mapped in Figure 1 shows a sequential pattern beginning with plant reproduction and progressing to methods of fauna reproduction. Furthermore, the student stated some concrete examples of biological reproduction, such as beans, roses, birds, and snakes. Moreover, recurrent arrows are inserted that link revisited ideas to the earliest step where the related idea first occurred. Statement 3, for example, 'beans use their seeds for reproduction' includes one major revisited idea 'seeds for reproduction'. Therefore, statement 3 has one recurrent arrow drawn back to statement 1 (the earliest step containing a statement about seeds for reproduction; for further details about the flow map method, see Anderson and Demetrius, 1993; Anderson *et al.*, 2001; Tsai, 1998a, 2000, 2001). A flow map representation exhibits both the sequential pattern of recall and also evidence of an underlying interconnected texture of ideas in cognitive structures. The flow maps provide researchers with information about the complexities and idiosyncrasies of an individual's cognitive structures, and organisational schemata as represented by the evidence of connected knowledge contained in the flow map data (e.g., Bischoff and Anderson, 2001).

The following two variables representing knowledge construction are obtained from the flow map data:

- *Linear linkages*: the number of ideas and their sequential organisation as shown in the flow map, an indicator of the extent of recalled knowledge (8 in Figure 1).
- *Recurrent linkages*: the number of revisited and linked ideas indicated by recurrent linkages shown in the flow map, an indicator of the richness of knowledge networks within a student's cognitive structure (5 in Figure 1).

There were a total of four flow-map interviews in this study. The first three interviews were conducted at the end of each week of instruction. The final interview was conducted two months after the instruction to obtain evidence of longer term retention of knowledge. Figure 1 is a student's flow map obtained from the third interview. The same student's flow maps obtained from the first, second, and final interview are shown in Figure 2, Figure 3, and Figure 4, respectively. The reliability of flow map diagramming was determined by asking a second independent researcher to diagram a subset of the student interview narratives. The inter-coder agreement for sequential statements (i.e., linear linkages) was 0.89 and for recurrent linkages was 0.83. (For the calculation of the reliability coefficient, please refer to Anderson and Demetrius (1993).) Based on this evidence, this method was deemed to be sufficiently reliable for the purposes of this research study. In general, reliabilities greater than 0.80 are considered sufficient for narrative analyses.

This study also used content analysis methods to examine students' cognitive operations and information processing strategies based on the flow maps. Each of the students' ideas, shown in the flow maps, was categorised into one of the following five levels of information processing modes:

- *Defining*: Providing a definition of a concept or a scientific term, e.g., Oviparity indicates animals that lay eggs and hatch outside the mother's body.
- *Describing*: Depicting a phenomenon or a fact, e.g., Some snakes' reproduction is by oviparity, but some snakes' reproduction is by ovoviviparity.
- *Comparing*: Describing the relationships between (or among) subjects, things, or methods, e.g., Compared to other methods of reproduction, the oviparity could generate more offspring at one time.
- *Conditional Inferring*: A description about what will happen under certain conditions, e.g., If the pollen deposits onto a pistil, it may generate seeds.
- *Explaining*: Presenting an account to justify the causality of two facts or events, e.g., Since the oviparity lacks parental care, it needs a large amount of eggs to increase the survival rate.

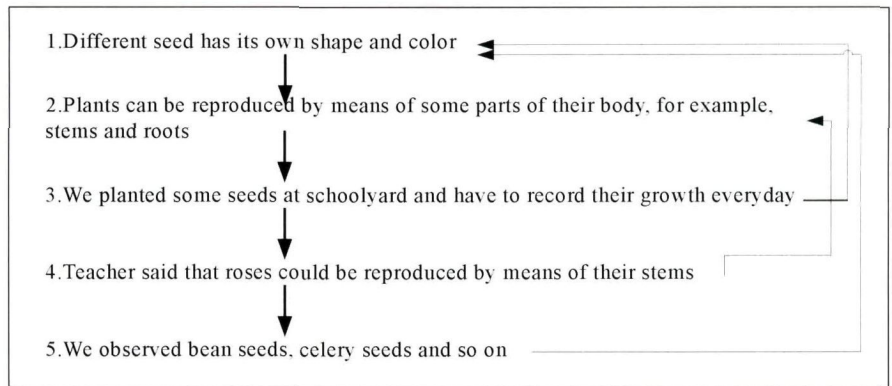


Figure 2 John's flow map obtained from the first interview.

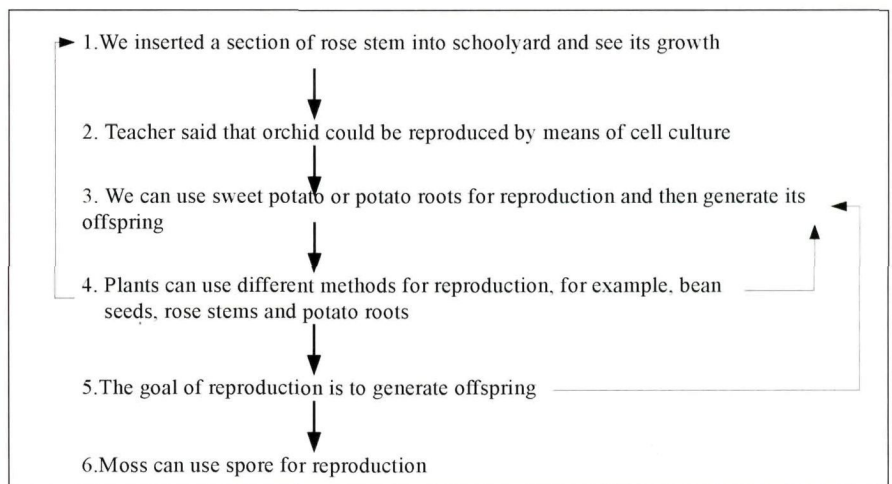


Figure 3 John's flow map obtained from the second interview.

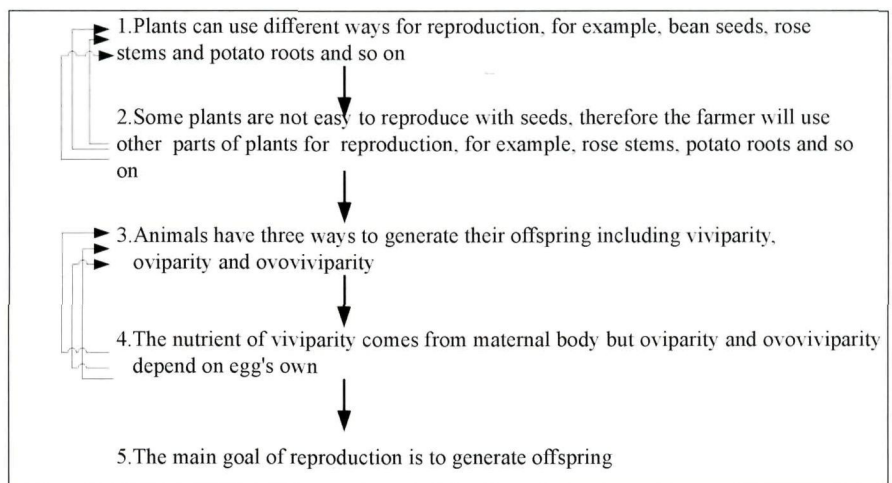


Figure 4 John's flow map obtained from the final interview.

This categorisation scheme was the same as that used in Tsai (1999a, 2001). The purpose of the information processing analyses was to acquire a deeper understanding about a student's reasoning when (re)constructing science knowledge. A total count of the coded statements occurring in each of the categories was obtained by examining the statements in the flow map narrative. Students who frequently use higher-order modes of information processing (e.g., 'explaining') were viewed as having better strategies for organising information during recall. An inter-coder reliability of 0.88 was obtained for the content analysis. (This means that the two coders had the same way of categorization on 88% of students' ideas). After the reliability

analysis was completed, those statements that lacked inter-coder agreement were discussed between the two coders and consensus reached.

Results

Table 1 presents data on student cognitive structure outcomes and categories of information processing modes gathered from the four consecutive interviews. This study showed that the extent of students' cognitive structures (i.e., linear linkages) increased as a result of the instruction; however, two months after instruction, the linear linkages shown in the flow maps regressed to almost the original amount as elicited in the first interview (5.18 at the final interview versus 5.14 in the first interview). The finding is somewhat consistent with a conclusion commonly revealed in science education research that students return to almost their original conceptual frameworks some time after the instruction (Wandersee *et al.*, 1994; Tsai, 1998b, 1999b). It is also consistent with classical studies on memory that show a decline in available recall knowledge with time. However, the recurrent linkages showed some encouraging findings. Students' recurrent linkages increased from the first interview to the second interview, but remained stable after the second interview. This implies that the recurrent linkages, that is, the richness of student cognitive structures represented by interconnected ideas, may not decay rapidly even some time after the instruction. In other words, the extent of the knowledge store in memory may decrease relatively soon after the instruction, but the richness of knowledge networks may remain in long-term memory and exhibit more consistency.

Student information processing strategies also showed some interesting trends across the interviews. For example, the 'defining' mode of information processing was detected frequently during instruction (mean = 0.64, 0.50, and 0.57 for the first three interviews respectively), but rarely used two months after the instruction (mean = 0.18). A similar result was found for the use of the 'describing' mode which was the least used in the final interview. This suggests that the lower-level information processing modes such as 'defining' and 'describing' may be more frequently exhibited during knowledge construction but less prevalent in later recall. These categories may not be exhibited in later recall narrative, because students, at this point of knowledge maturation within this particular domain of information, use higher-level modes in organising knowledge, thus enhancing the integrity of knowledge networks and facilitating efficiency in information retrieval and application. The increased occurrence of the 'inferring' and 'explaining' categories that reached a maximum two months after the instruction appears to support this conclusion. In particular, the use of 'explaining' increased as the instruction progressed, and its frequency in

Table 1 Student cognitive structure outcome and information processing modes across interviews (n = 28).

	<i>First interview</i> Mean (SD) [Range]	<i>Second interview</i> Mean (SD) [Range]	<i>Third interview</i> Mean (SD) [Range]	<i>Final interview</i> Mean (SD) [Range]
Linear linkages	5.14 (6.95) [1 – 34]	5.50 (6.71) [1 – 31]	5.61 (4.86) [1 – 21]	5.18 (5.24) [0 – 22]
Recurrent linkages	3.29 (5.59) [0 – 21]	4.64 (7.08) [0 – 26]	4.54 (5.44) [0 – 23]	4.54 (7.20) [0 – 33]
Defining	0.64 (0.68) [0 – 2]	0.50 (0.88) [0 – 4]	0.57 (0.79) [0 – 3]	0.18 (0.39) [0 – 1]
Describing	3.57 (4.84) [0 – 24]	3.71 (4.22) [0 – 18]	3.54 (2.52) [1 – 11]	3.04 (2.63) [0 – 12]
Comparing	0.18 (0.61) [0 – 3]	0.43 (1.00) [0 – 4]	0.96 (1.99) [0 – 10]	0.71 (1.33) [0 – 5]
Inferring	0.61 (1.34) [0 – 6]	0.68 (1.39) [0 – 6]	0.32 (0.86) [0 – 4]	0.79 (1.73) [0 – 8]
Explaining	0.14 (0.59) [0 – 3]	0.21 (0.50) [0 – 2]	0.21 (0.69) [0 – 3]	0.50 (1.37) [0 – 5]

the final interview was more than double the previous one (0.50 in the final interview versus 0.21 in the third interview). This indicated that students seemed gradually to (re)construct their knowledge frameworks through higher-order modes of information processing after instruction and, perhaps, these higher order modes of representation helped to increase the generalisability and inclusiveness of the information.

Table 2 presents the correlation coefficients among student cognitive structure outcomes and information processing strategies. These correlational analyses were based on the research data gathered from the third interview. The third interview was conducted immediately after the instruction; hence, students were likely to have the richest store of available knowledge and thus sufficiently varied information in their recall narratives to support a robust correlation analysis. Table 2 shows that the extent of student cognitive structures (linear linkages) was significantly correlated with all modes of information processing. This suggests that the extent of available knowledge during recall is an important concomitant variable in supporting a variety of information processing strategies. The number of recurrent linkages, a major indicator of networking in recalled knowledge, was significantly correlated with the use of 'describing', 'comparing', 'inferring', and 'explaining', but not 'defining'. Moreover, among these correlations, the coefficient was relatively low between recurrent linkages and 'describing'. This may imply that the richness of information network linkages in cognitive structures (recurrent linkages) is more likely to be

Table 2 The relationships between cognitive structure outcomes and information processing modes based on the data gathered from the third interview (n = 28).

	<i>Linear linkages</i>	<i>Recurrent linkages</i>	<i>Defining</i>	<i>Describing</i>	<i>Comparing</i>	<i>Inferring</i>
Recurrent linkages	0.93**					
Defining	0.43*	0.33				
Describing	0.77**	0.55**	0.31			
Comparing	0.65**	0.83**	0.13	0.09		
Inferring	0.83**	0.75**	0.21	0.53**	0.50**	
Explaining	0.85**	0.81**	0.10	0.53**	0.60**	0.94**

*p < 0.05, ** p < 0.01

related to higher-level modes of information processing. That is, the number of recurrent linkages could be a good predictor in explaining student use of higher-level information processing strategies, such as 'inferring' and 'explaining'. Table 2 also shows that the use of 'defining' was not significantly related to the use of

other information processing modes. However, students who more frequently phrased their ideas in the mode of 'explaining' tended to use 'describing', 'comparing', and 'inferring' more frequently. This suggests that the use of 'explaining' may mutually enhance the use of other information processing strategies.

Discussion and educational implications

Based on the flow map analyses of the fifth grade students' narratives, this study showed that students' knowledge storage decreased two months after instruction; however, the richness, or degree of interconnection of knowledge during recall, did not show a similar decline. Teachers should encourage students to make connections between concepts to stabilise as much information as possible while supporting the higher order information processing modes as described later. The decrease in linear linkages found in later interview data, coupled with almost no change in the number of recurrent linkages, also suggested that students seemed to build up more integrated conceptual frameworks after the instruction.

Content analyses of student information processing strategies showed that students' lower-level modes of information processing decreased and higher-level modes increased as instruction progressed and also in the interval after instruction. In particular, the highest mode, 'explaining', was used most in the final interview (i.e., two months after the instruction), while the lowest mode, 'defining', was rarely found in the final interview. This may imply that students tended gradually to refine their knowledge structures by a series of reformulations involving use of explanations, principles, and generalisations, but with less emphasis on definitions or descriptions. This refinement may help students to organise the concepts more effectively, and reduce cognitive load when retrieving or applying these concepts. This interpretation is also consistent with the previously stated finding that students tended to construct more integrated knowledge frameworks in the weeks following instruction. The use of higher-level information processing strategies and the increase in networking connections among existing concepts may mutually reinforce one another and, at the same time, help to refine or condense the body of knowledge, therefore, in turn, yielding a more integrated body of knowledge in memory. Hence, biology teachers are encouraged to promote students' higher-order cognitive operations. Tsai (2001) has suggested that the use of Prediction-Observation-Explanation (POE) instructional activities, Socratic dialogues, and interactive ques-

Table 3 A model of the processes of student cognitive structure development.

	Interview 1 to 2	Interview 2 to 3	Interview 3 to 4
Stage	Knowledge development	Knowledge extension	Knowledge refinement
Stage feature	Both the extent and the richness of cognitive structures increase.	The extent of cognitive structures keeps increasing; however, the richness and the use of high-order information processing modes do not necessarily increase.	The extent of cognitive structures decreases, while their richness remains stable. The use of higher-order information processing modes increases dramatically.

tioning may be useful for enhancing students' information processing levels.

The data gathered from this study suggest a three-stage model for the acquisition of science knowledge, at least as exhibited with this particular learning situation. These stages are 'knowledge development', 'knowledge extension', and 'knowledge refinement' as shown in Table 3, and further illustrated in Figure 5. In the first stage, both the extent and the richness of cognitive structures increase; that is, the knowledge storage and connections among concepts are developed. In the second stage, only the extent of knowledge in cognitive structures keeps increasing; however, the richness of interconnections and the use of higher-order information processing modes do not necessarily increase. Therefore, in this stage, the main focus of knowledge construction is apparently an extension of the existing body of knowledge. In the final stage, which may occur some time after the instruction, the extent of information recalled decreases, while the richness of interconnections in the networked knowledge remains stable. At the same time, the use of higher-order information processing modes increases dramatically. Students, in this stage, may refine their knowledge structures into more integrated frameworks through more sophisticated cognitive operations. In other words, the rich connections between concepts and the use of higher-order information processing strategies facilitate the maturation of knowledge reconstruction and refinement. (Or vice versa, that is, the maturation of knowledge reconstruction and refinement may enhance the connections among existing concepts and the use of higher-order information processing.) This model is based on the research data collected by this study and, clearly, more research is necessary to examine the generalisability of this model. Nevertheless, this model gives educators some clues about the processes and mechanism of student knowledge development in science, especially at an early age when impor-

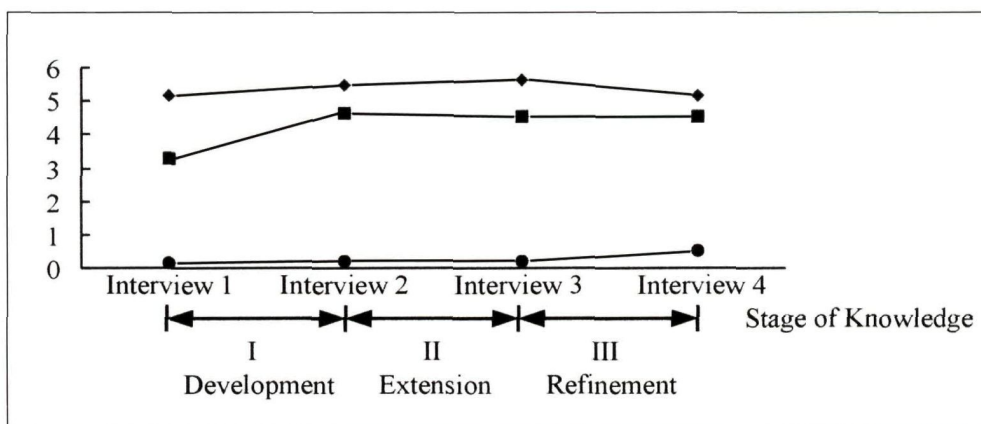


Figure 5 The stages of knowledge acquisition suggested by the study. ◆ Linear linkages ■ Recurrent linkages ● Explaining

tant knowledge structures and orientations toward science are being constructed by the learner.

The correlation analysis between cognitive structure outcomes and information processing strategies also revealed that an adequate body of interconnected knowledge and a variety of information processing strategies may mutually reinforce one another. Students' use of 'explaining' was also strongly related to the number of linear linkages and recurrent linkages, and their use of 'inferring'. This implies that the use of 'explaining' may be developmentally linked to the richness of interconnected ideas in cognitive structure during short term learning experiences and may be dynamically linked to other higher-level information processing strategies as the learners reconstruct and solidify information in memory.

This study also suggests some research issues for further exploration. For example, it may be interesting to explore to what extent did the students recall the information in a sequence that was comparable to the sequence of instruction by the teacher across the three weeks. In addition, more research work can be conducted to see whether students who exhibit greater evidence of interconnected thought and use of higher-order cognitive operations sequenced their thoughts in a different way from other students.

In conclusion, this study showed some evidence that elementary school students, who learned about biological reproduction, gradually developed more integrated knowledge structures as represented by recall narrative, which were also accompanied by evidence of higher-level modes of information processing. This study also demonstrates that through the use of the flow map method, biology teachers can assess student cognitive structures and information processing orientations, and use such information to identify the cognitive development, misconceptions, strengths, and weaknesses of each student's knowledge growth within a specific scientific topic. The findings derived from this study also suggest that biology teachers need to encourage students to use higher-level information processing and, concurrently, to develop richer and more integrated knowledge frameworks during biology instruction.

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