A comparison of the developmental patterns in students' responses to questions in mathematics and science.

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This paper reports on a comparison of the results of two studies which involved the testing and interviewing of students from Year 3 to Year 12 in New South Wales schools. The targeted topic areas were Geometry (2-D figures) and Biology (plant growth). The SOLO Taxonomy was used as the vehicle to categorise the responses. The results in both studies identified cycles of development in the students' answers. The purpose of this article is to explore the differences and similarities between the cycles and provide a window into how students' conceptual understandings develop.

Introduction

Assessing students' understanding in the fields of Mathematics and Science has been receiving increased attention in the research literature. One impetus for this focus has been the realisation that many of the long accepted methods of assessment actually encourage inappropriate teaching and learning methods. The distortion to the learning process can be characterised by: rote learning of rules and procedures: and, the value placed on quantitative learning (i. e., excessive repetition of activities) rather than in the quality associated with the understanding of underlying principles.

One procedure which offers the potential to address this current imbalance in assessing students' understanding is the SOLO Taxonomy of Biggs and Collis (1982 and 1989). It is a categorisation system which attempts to address the quality of students' understanding in terms of a model of how students learn. Before considering two examples (one in Mathematics and one in Science) of how the SOLO Taxonomy might be applied, it is appropriate to describe briefly key aspects of the model.

The Model

The SOLO Taxonomy is a classification framework with its roots in the Piagetian tradition. There are two basic elements to the Taxonomy. The first is a series of five modes of intellectual functioning. The second is a series of levels of attainment which are repeated within each mode. The five modes of functioning can be described as follows:

Sensori Motor - a person reacts to the physical environment. For

the very young child it is the mode in which complex motor skills are acquired. These play an important part in later life as skills associated with various sports evolve.
Ikonic - a young child develops words and images which can stand for objects and events. For the adult this mode of functioning assists in the appreciation of art and music and leads to a form of knowledge referred to as intuitive.
Concrete Symbolic - a person thinks through using a symbol system such as written language and number systems. This is the most common mode addressed in the upper primary and secondary school.

Formal - a person considers more abstract concepts. This can be described as working in terms of 'principles' and 'theories'. Students are no longer restricted to a concrete referent. In its more advanced form it involves the development of disciplines.
Post Formal - a person is able to question or challenge the

fundamental structure of theories or disciplines.

Figure 1. Adapted from: Biggs, J.B. & Collis, K.F. “Multimodal learning & the Quality of Intelligent Behaviour” (1989).

One important difference between these SOLO modes and the work of Piaget, is the belief that persons can function in more than one mode, and that there are many opportunities for persons to use different modes to support learning in another mode. In Figure 1, examples of different forms of learning involving modes are indicated by horizontal and vertical arrows. Obviously, there are numerous possible combinations of these forms of learning, involving different groupings of modes.

Associated with each mode is a series of levels. These are referred to as: unistructural (U), where a person focuses on one aspect of a question or stimuli; multistructural (M), where a person focuses on several aspects but does not see relationships between the aspects; and, relational (R), where a person can see interconnections between various aspects. The cyclic pattern, within modes, of the U-M-R levels is indicated in Figure 1.

It is sometimes useful when discussing responses within a mode to refer to two other levels. They are: prestructural, when the person is not able to respond to a question in a meaningful way; and, extended abstract, where the person can bring new information to the problem from outside of the question. This latter level, when applied to some response in a given mode, can also be equated with the unistructural response in the next mode. For simplicity, both levels have been omitted from Figure 1.

The levels associated with the SOLO Taxonomy have several properties as the focus shifts from unistructural to relational which include:

1. a growing complexity in understanding;
2. an increased ability to consider more information;
3. an increased ability to accept complexity;
4. an increased ability to delay in providing an answer.

Other features of the model include: the levels are sequential and students cannot jump or skip levels; the language used by students changes as they proceed through the levels and modes; and, there are characteristic ways of thinking at different levels. It has also been noted that students can choose to work at a lower level for a variety of reasons, e.g., lack of motivation.

Background to Studies

The application of the Taxonomy to a variety of domains has been achieving increased interest in the research literature. As a result of the work of a number of researchers, empirical evidence in topic areas in a number of subjects is being gathered which is explicating more clearly the modes and levels. One relatively recent issue of research has been the nature of the development of a concept within a mode. The result of these investigations (see for example, Campbell, Watson and Collis, 1992; Levins, 1992; Levins & Pegg, 1993; Pegg, 1992) has been the identification of more than one unistructural - multistructural - relational cycle within a mode. The topic areas used for these investigations were: Volume - Campbell et al.; Plant Growth/Evaporation - Levins; and, Geometry/Algebra/Statistics - Pegg.
In general the findings of the studies have been similar. That is, the investigations have identified that a large number of students in both upper primary and secondary school operate in a way that suggest there are at least two recognisable cycles in the concrete symbolic mode. Such results have important implications for the accurate interpretation of student performance and the planning and sequencing of concepts in instruction. However, much more is needed to be known about the nature of the cycles before the potential of these findings can be realised in practice.

The remainder of this paper addresses this issue in two sections. The first provides an overview of the results identified by Pegg in Geometry, Levins and Pegg in Plant Growth in an attempt to provide empirical evidence for the cycles identified. The second section explores the metaphors offered by the different studies which were developed to explain the nature of the cycles and compares these metaphors with the one developed by Campbell et al.

The Studies

The Mathematics Study

This study consisted of a questionnaire surveyed across students ranging from Year 3 to Year 7, i.e., 8-13 year olds from schools in Queensland and New South Wales (see Pegg & Davey, 1988). The students were asked to draw a square. Students were then asked to give their best description of the figure. This was repeated for some other 2D figures, i.e., rectangle, parallelogram and rhombus. A sample of students was interviewed to test the robustness of the students' written response.
Results

The responses were classified into homogenous groupings. In all, five broad groupings of responses, coded A - E, were found. Typical examples of student responses for the four figures in each group are provided below.

Category A

The students' answers focused on the global image of the shape.
Square: "it (h)as to (be) even on each corner"
Rectangle: "it is almost the same as a square but it is larger"
Parallelogram: "it is like a rectangle that has been pushed to one side"
Rhombus: "is a square on a lean".

Category B

The students in this group focused on the lines. However, it was also common for the students to provide some reference to a global image as if to offer additional support for their answers.
Square: "straight lines its a flat shape"
Rectangle: "4 straight sides"
Parallelogram: "it has four sides"
Rhombus: "4 sides but they are diagonal".

Category C

The students in this group had improved slightly on those from Category B. It was as if they knew that mentioning lines was not sufficient. The students here tried to provide some qualification although they were unsuccessful. It is worth noting that there were no responses obtained in this category for either a square or a rhombus.

Square: no responses recorded
Rectangle: “is simuler (sic) to the square but the sid (sic) are longer than the two on the top and bottom
Parallelogram:“is like a rectangle except tilted to one side a bit and the two end sides face the same way”
Rhombus: no response recorded.

Category D

The focus of the responses in this group is also predominantly on straight lines but there are real attempts to provide the key characteristic, namely, equality.

Square: “4 even lines”
Rectangle: “two sides are longer than the other two, four corners, smooth sides”
Parallelogram:“the two sides are the same. But the other two sides are on a slant”
Rhombus: “is like a half squashed all sides are equal”.

Category E

The student responses in this category focused on more than one property of the figure. These type of responses would be, in general, the best that could be expected from students answering this question. The reason for this being the word ‘describe’, in this context, implies that what is required is a list of all the ‘aspects’ that are known about the figure.

Square: “is a shape that has 4 sides and 4 angles. The angles are all 90 degrees. All sides are even and equal to each other”
Rectangle: “has all parallel sides. The angles are all 90 degrees. Two lines are the same but are larger than the other two lines”
Parallelogram:“has 4 sides two of them are equal to each other the other two are equal to each other. If you run the lines forever they will never meet”
Rhombus: “has 4 equal sides and 4 equal angles* is also called a diamond”. (* note: in the interview the student clarified that 4 equal angles meant equal in pairs)

The analysis of the categorisation of the groups of responses, identified two main features when considered within the framework offered by the SOLO Taxonomy. The first feature concerned category A. Here, the responses focused on the global nature of the figures. Students described the given figures in terms of known shapes. Some features were mentioned, such as, corners. However, these were also global notions. During interview sessions students would refer to “corners of rooms” to explain what they meant. These characteristics of the response are indicative of those associated with the ikonic mode.

The second feature of the responses concerned the remaining categories. Category B, C, and D showed a gradual evolution of the notion of a single property. The groupings satisfy the unistructural, multistructural and relational levels, respectively. Category D responses can be interpreted in two ways. They can be seen as providing some overview of the features, i.e., sides and equality. In the second case, this coding would represent a unistructural level response, i.e., a focus on one property. This is then followed by category E in which students’ responses provided several properties.

In summary, a two cycle pattern became evident. In the first cycle, students focused on what could be described as the features of the geometric shape, e.g., the sides of a square and the quality of the side. There is a definite development of ideas towards the relational level for example when the students'

responses reflect their ability to relate all the ideas about one property that describes a figure. The first cycle appears to develop the idea that a certain characteristic of a figure is invariant.

The students responding in the second cycle progress to identify other properties that are necessary for the correct description of a geometric shape, i.e., other properties, e.g., right angles that exist as a characteristic for the description of the geometric figure-a square. The second cycle develops on the base line established in the first cycle and identifies a number of properties, that are characteristic for particular 2D geometric figures.

The above description can be summarised in a diagram as follows in Figure 2.

Figure 2. Two cycles within concrete symbolic mode.

The Science Study

To investigate ideas associated with plant growth, a short questionnaire was developed. It consisted of a reference diagram (see Figure 3) and five questions. This specific diagram was provided so that both the younger and older students had the same diagrammatical configuration from which to work. It was felt that the diagram would assist in directing students' ideas while, at the same time, allowing students to answer the questions according to their individual meanings of the words "plant growth".

Figure 3. Reference diagram for the investigation of ideas associated with plant growth

The five questions used in the study were:

1 If you were asked to give an explanation suitable for a Science dictionary, how would you explain plant growth?

2 How would you know if the plants were growing?

3 What 'things' would the plants need to take from the surroundings to help it grow?

4 In as much detail as you can, explain how the necessary 'things' that the plants take from the surroundings help the plants to grow?

5 Explain how photosynthesis is a necessary part of a plant's growth?

Several important features were built into the set of questions. There was a deliberate attempt to relate the questions to the students. That is, the emphasis was on students providing their personal views/ideas about the questions rather than learnt responses. In particular, question 1 and 2, attempted to establish this context for the answers. The questions were also designed to elicit 'open' and 'closed' responses. Questions 1 and 5 were 'open' in nature. Here, the questions were asked to try and prompt a sequential development of the responses that could be offered by the students.

Results

Again, as in the Mathematics study, the analysed responses to the questions could be classified into homogenous categories, according to like responses. These are provided below under seven headings, categories A - G.

Category A

Responses which were classified into this category were those in which students denied any understanding of the question, answered tautologically or refused to respond. For example, to the instruction, "Explain how photosynthesis is a necessary part of plant growth", typical responses were: "So we live."(Year 7); "…if it didn't have it, we would die" (Year 9).

Category B

In this category, students were capable of recalling only one aspect to answer the question. For example, one Year 9 student wrote,"…how much a plant would grow in a certain period of time". This statement indicates that the student understands that time is a necessary feature of plant growth.

Another response focuses on the feature of size, e.g.,

"…is a measurement that a plant would show" (Year 10).

Category C
Responses were classified into this category if the student described two or more features, which would be necessary for a plant to grow. "What 'things' would the plants need to take from the surroundings so that they could grow?" Two examples of such responses to the question are,"…H2O, CO2 and soil" (Year 8) and "Water, soil, sun" (Year 7).

Category D
The students who responded in this category were able to draw conclusions and form generalisations. They could make linkages and identify relationships between features necessary in the growth 'process'. For example: Given the instruction "In as much detail as you can, explain how the necessary 'things' that the plant takes from the surroundings help the plant to grow", typical responses were: "…through photosynthesis, nutrients and water are converted to starch and then cellulose to be used as building blocks for the plant" (Year 10); "…they use photosynthesis, which means the supply of light, soil and air, so the plant can make its own food" (Year 7).

Category E
This category of responses reflects an understanding of the process of photosynthesis required for growth, but no linkages are made between the reactants in the process and the products which ultimately provide the materials necessary for plant growth. For example: When asked "If you were asked to give an explanation suitable for a Science dictionary, how would you explain plant growth?" A typical response at this level was: "…the plant will need water and sun light to grow. As it grows it will take in CO2. The leaf is where the plant makes its own food using photosynthesis" (Year 7).

Category F
Responses in this category reflected on overall understanding of the photosynthetic process and intermediate processes involved. To illustrate this, a typical response from a Year 10 student follows: "Plant growth is the way a plant creates more of itself by absorbing external matter. Plants achieve this by using the process photosynthesis, whereby chlorophyll in the leaves, nutrients and water from the soil, and CO2 are combined by energy

from the sun to form simple sugars that the plant uses to build itself".

Category G

The student responses (there were very few) which were coded into this category, showed a far greater degree of understanding than

responses classified in any other category. The responses classified into this category reflect the fact that the students were able to understand the underlying processes (photosynthesis and cellular respiration) necessary for plant growth, i. e., they were able to deal with abstract ideas and relate them to the concrete world. An example identified was: "Plants convert; CO_2 + H_2O + Energy > glucose + O_2. This is very important because plants waste product is O_2 and this is essential for animals to breathe. The glucose which is produced by the plant is often stored as starch, however, when the plant uses glucose (respiration), this allows the cells to live, grow and reproduce" (Year 12).

In this response the student has shown a fuller understanding of plant growth. With the inclusion of the process of respiration in the answer, the student has brought in information from outside the context of the question to explain the concept of plant growth more fully.

It became evident in this study that the students' responses could be classified at two 'levels'. Firstly, the unistructural, multistructural and relational descriptors could satisfy the student responses in Category B, C, and D respectively. For example in answer to question 3 above, the student responded by focusing on soil or water or size, (i. e., one feature surrounding the concept of plant growth). This would be classified as unistructural.

The second finding was again similar to that in the Mathematics Study. There became evident a definite, discernible two cycle pattern in the concrete symbolic mode. In the science investigation the second cycle is clearly described by the students showing an understanding of the processes involved in the scientific idea of plant growth. The responses allocated to Categories D, E, and, F were characterised by their increased awareness of the necessary processes underlying the actual growth of a plant. This can be depicted by Figure 4 below.

Figure 4. Two cycles within the concrete symbolic mode

The responses placed into Category G showed an understanding that brought ideas from ouside the context of the question, such as, the students who felt it was necessary to "talk" about respiration to fully explain plant growth. This Category was placed into the Formal mode.

The results from this study support the conclusion that students require the first cycle to build the basic concepts, i.e., students' responses reflect reality as they perceive it. These foundation ideas underpin the development of the more demanding cognitive abstraction of ideas into process-orientation. With reference to the specific concept, plant growth, the first cycle describes the concrete features involved in plant growth and the second cycle describes how these features are used in the process of photosynthesis. This chemical process is only one necessary for plant growth, but almost exclusively, it was the process mentioned in the responses collected in this research. Perhaps photosynthesis is the process that teachers concentrate on in the classroom.

Comparison of Results

Both the Mathematics and the Science study resulted in a cyclic pattern in response development within the concrete symbolic mode. Since this is the mode within which most schooling takes place, it would seem important to interpret these results within the bounds of student learning and conceptual understanding.
The first cycle, in both disciplines, is fundamental to further understandings of concepts. This cycle is bedded in the concrete world, i. e., in Mathematics, the student is able to relate to one important visual feature that they believe determines a 2D geometric figure; in Science, the student is able to relate to 'things' he/she can 'see' surrounding plant growth, e. g., increase in size.
In both disciplines this first cycle identified, links closely with thought processes associated the ikonic mode. That is, the students' responses relate closely to images. In 2D Geometry it was the focus of attention on the most obvious feature of figures, the sides that heralded this change. In the case of Plant Growth it was the features that surround a plant, for example, air, soil and sun that are first identified. In both cases, there is a clear move away from reliance on affect-laden imagery.
It would appear that the students whose responses are classified into the categories in the first cycle are in a state of transition. Their responses show features of being able to think more abstractly than in the ikonic mode, but their responses reflect a reliance on imagery to reinforce their answers. The

students are more confident about their response when 'allowed' to think in 'pictures'.
As the response categories shift from unistructural, multistructural to relational, more conceptual understandings are reflected in the response groupings. This increase in the ability to conceptualise is continued into the second cycle in both studies. The students' responses reflect an increase in the abstraction of ideas.

Comparison of models
In the studies described above, two different metaphors were developed to explain the results identified (see Figures 2 and 4). A third model has been offered in the literature and has grown out of work reported on Volume concepts by Campbell et al (1992). The diagrammatic representation they proposed is provided in Figure 5.

Figure 5. Development within the Concrete Symbolic Mode.

The final part of this paper explores the similarities and differences in the three models as a way of identifying further research issues.

1. 2D Geometry and Plant Growth

The two models (Figures 2 and 4) have much in common. In particular, they both identify as equivalent the relational level in the first cycle and the unistructural level in the second cycle. However the models do suggest that, despite their equivalence, there may be some differences in these two levels. Also, implied in the models is that while development from R2 may be to a U3 in the concrete symbolic mode, it is anticipated that the next category of quality of response would be a unistructural response in the next mode (Formal Mode). The major difference between the models was the observation in the study of concepts surrounding Plant Growth, that the second cycle picked up and expanded on aspects identified by students in the first cycle. There was no indication of this at all in the 2D Geometry study.

2. Plant Growth and Volume

The proceeding point, i.e., the elaboration of simple concepts in the first cycle in Plant Growth being developed in the second cycle, was not a feature of the study involving volumes. Also, the volume study diagram did not make explicit development between R1 and U2. Instead, it accepted equality of the two forms of response. The major difference in the diagrams was the hypothesis that there should/could exist a Formal response evolving out of the first cycle. The results of the Plant Growth study suggest, given the nature of the first cycle, that there would be little if any possibility of a formal response evolving out of this early cycle.

3. 2D Geometry and Volume.

The point of a Formal response observed from the first cycle was also at variance with the model proposed for the 2D Geometry. The major similarity here was the acknowledgment (made explicit in the volume study), that new aspects enter into the second cycle that have not been identified by students as relevant in the first cycle. This is counter to the findings in the Plant Growth study.

The analysis of the three models offers a number of interesting research questions which would elaborate more clearly the nature of the development of concepts within a given mode. Three important questions are:

1. Are responses categorised as R1 and U2, within a given mode, equivalent or are there some qualitative differences in the answers which reflect different understandings of students?

2. Is it possible to identify a mode shift from the first cycle. That is, can instances of responses be identified that indicate a development from R1 (concrete symbolic) to U1 (formal)?

3. Why is it that in some topics, important features in the second cycle are not referred to by students in the first cycle?

Conclusion

This paper has offered empirical evidence to substantiate the claim that there are at least two cycles of growth within the concrete symbolic mode. This result has important implications which offer the teacher a clearer insight into how students' understanding might develop. The first cycle represents a transition from visual thinking into the concrete symbolic mode. The second cycle identifies what many secondary teachers would see as the main focus of activity in the secondary school. In 2D Geometry it would be the consideration of the invariant features of figures, while in Plant Growth it would be the processes associated with scientific phenomena.

Also considered was the implications, to further understanding of the cycles, of the three metaphors used as summaries to the findings of several investigations. Differences and similarities were identified in the models which lead to the formation of three research questions. It would appear that the results of studies developed to respond to these questions would be very valuable. They would not only help the process of more accurate assessment but would assist in the planning of a more appropriate learning and teaching environment.

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