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INVESTIGATING STUDENTS' UNDERSTANDINGS OF DIFFUSION AND OSMOSIS: A POST-PIAGETIAN ANALYSIS

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ABSTRACT

Diffusion and osmosis are two concepts that are fundamental to a study of biology at both a secondary and tertiary level. Both these concepts cause difficulties for students as demonstrated by the alternative conceptions held by students identified in numerous documents in the research literature (Okeke & Wood-Robinson, 1980; Westbrook, 1987;

Odom, 1992; Zuckerman, 1993). A critical aspect of the understanding of these processes is their abstract nature and it appears that it is this feature which lies at the root of the problems faced by students. However, the nature of the development of these abstract ideas has not been chartered, nor has a comparison of the development for each concept. This paper offers an initial attempt to both discern, and compare and contrast the developmental growth of these concepts with 60 year 11 and 12 students. The SOLO Taxonomy was used as the evaluative tool which provided the theoretical basis to explore the answers to a series of open-ended questions.

INTRODUCTION

In an investigation of students' perceptions of biological processes, Okeke and Wood-Robinson (1980) found that only 37% of students aged 16-to-18 years recognised diffusion and osmosis as opposite concepts. During the last two decades this finding, together with concern regarding the difficulties associated with these concepts, has initiated a number of investigations into students' understandings of these two concepts. One of the earliest was undertaken by Friedler, Amir and Tamir (1985). They found that the majority of 142 students in Years 9, 10, and 11 included in the research sample, could not explain 'why' either of the two processes occurred and could not distinguish between them. Similarly, Marek (1986), who sampled 60 students in 10th grade, discerned that only 37.5% of students demonstrated any degree of understanding of the diffusion concept.

Later studies have tended to focus upon students' conceptions of diffusion and osmosis. A number of these have attempted to examine the influence of factors, such as intellectual development (Westbrook, 1987), the year of education (Simpson & Marek, 1988), gender (Odom, 1992), the size of school attended by the student (Simpson & Marek, 1988), and the length of course undertaken by the student (Odom, 1992) on students' understandings of diffusion and osmosis. However, only the latter two emerged as discerning variables.

In relation to students attending large high schools (i.e., exceeding 900 students), a higher level of understanding was demonstrated by these students than by students attending small high schools (i.e., less than 150 students). This occurred even though the students shared a common socioeconomic background, identical textbooks, backgrounds in science, and a lack of exposure to the concept of diffusion. Clearly, these results indicate there may be a range of less obvious factors influencing students' understandings of science concepts, such as pedagogy and the scientific understanding of science teachers. In terms of the second discriminating factor, i.e., the level of course undertaken by the student, Odom (1992) identified that college students undertaking five semesters of biology demonstrated higher levels of understanding of diffusion and osmosis than students involved in two semester courses. While this appears to be an obvious outcome, it did not support the earlier work by Friedler, Amir and Tamir (1985), Simpson and Marek (1988), and Westbrook and Marek (1991) who found no significant improvement in students' understandings of diffusion and osmosis as they progressed from secondary to tertiary education. It could be argued however, that the result from Odom (1992) emerged because students were undertaking biological courses rather than general science courses.

In contrast to this focus on individual factors, Noble (1991) and Zuckerman (1991, 1995) attempted to gauge whether problem-solving activities involving diffusion and osmosis initiated changes in students' conceptual understandings of these concepts. Results revealed no significant changes between students' pre-intervention and post-intervention conceptions. However, an important outcome from these studies was the identification of a number of alternative conceptions held by students in relation to diffusion and osmosis. These related to solubility, concentrations, permeability of membranes; random motion, and osmotic pressure.

Subsequently, researchers appear to have investigated students' understandings of diffusion and osmosis from a number of different perspectives. However, what has been lacking in the area is a pattern of cognitive development or growth for each of the concepts. One promising way of addressing this issue is through the interpretation of students' responses to questions using the SOLO Taxonomy. The reason for this is that in recent years, the SOLO model has achieved success in providing a necessary framework to help interpret student development in a range of subject and topic areas. It has been used in science to explore students' understandings of concepts related to evaporation (Levins, 1992), plant growth (Levins & Pegg, 1994), magnetism (Guth and Pegg, 1994), and speed (Cuthbert, 1996).

THE SOLO TAXONOMY

The SOLO Taxonomy, proposed by Biggs and Collis (1982; 1991), has evolved steadily since its initial formulation in the early 1980s. It now stands as a detailed model which can be used to explore and help interpret cognitive development in a range of learning areas. In so doing, it provides insights into the way understandings develop.

At the heart of the model are two key features, namely, modes of functioning and levels of achievement. There are five modes and their names together with a brief description of each is provided below.

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 person internalises actions in the form of images. It is in this mode that the young child develops words and images which represent 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 principles of theories or disciplines.

The mode most relevant to, and the usual target of secondary schooling, is the concrete symbolic mode. However, depending on student characteristics, backgrounds, and motivation, the ikonic mode may be discernible, either as a stand alone response or in some form of support to functioning in the concrete symbolic mode. For the more able performers early evidence of the formal mode is often apparent.

The second key feature of the SOLO model are the three levels, namely, unistructural (U), multistructural (M), and relational ®. It is significant that these levels (i) re-occur in each mode (Biggs & Collis, 1991), and (ii) that within a particular mode, they repeat in the form of multiple unistructural-multistructural-relational cycles. This however, has been identified in the responses of young students in a few topic areas (e.g., Levins & Pegg, 1994).

The relevance of SOLO to this present study is that it provides a framework upon which the structure of students' responses can be explored. It also offers the opportunity to investigate how these concepts develop and, in particular, whether a two-cycle approach can be identified from the responses of senior secondary science students, i.e., do some older students still respond within the first cycle in the concrete symbolic mode in the case of newly acquired information?

METHODOLOGY

In this study, 60 students undertaking Years 11 and 12 biology, and Year 11 3-unit science from two schools in NSW were invited to complete a series of five open-ended questions dealing with diffusion and osmosis. Initially, students were asked to define the two concepts in their own words. Then they were required to apply their scientific knowledge and understanding of diffusion and osmosis by addressing two separate biological problems involving each of these processes. Finally, students were asked to identify the similarities and differences between diffusion and osmosis.

In this paper, students' responses to the two application questions are analysed so as to address the following research questions:

1. Can a developmental path in students' understandings of diffusion and osmosis be identified using the SOLO model? If so, does the SOLO model provide a suitable framework to describe the development?
2. What are the key features of these developmental paths?
3. What are the differences and similarities between these two developmental paths?

RESULTS AND DISCUSSION

Students' responses to each of the questions were separated initially into categories based on the likeness of the response. These were then interpreted using the framework of SOLO to identify a sequence of levels of response. The results for the two questions are dealt with separately in the following discussion.

Question 1

Observe the following diagram representing a capillary surrounded by cells within the muscle tissue of a human. Identified within the capillary are glucose molecules.

See http://fehps.une.edu.au/F/s/curric/pg/dPanizzon/h.html

EXPLAIN the movement of glucose in this situation, giving as much detail as possible in your answer.

Eight categories of responses were discerned, representing a gradation from simple explanations involving a single sentence, to those of greater sophistication in which students demonstrated a deeper level of understanding of the diffusion of glucose.

CATEGORIES OF RESPONSES

Category A (Not codable)

Only blank responses were classified into this category and treated as missing data.

Category B (Direction of movement)

In this type of response, students had interpreted the diagram and were able to explain that glucose would move from the capillary into the interstitial fluid or into cells.

The movement of the glucose would be into the interstitial fluid.
(Student 42, Year 11 biology)
Students who responded in this category focused on a single feature in their explanations.
Category C (Direction of movement; steps involved) A number of sequential steps involved in the movement of glucose from the capillary into muscle cells, were identified in the responses coded into this category. This was achieved in one of two ways. Either the steps involved in the movement were listed, or these steps were provided using simple sentences. However, regardless of the style used, each of the responses communicated the same information as represented in the following example.

The glucose molecules travel down the centre tube and mixes with the

red blood corpuscle from there it passes through the capillary wall and

into all the body cells in muscle tissue.
(Student 40, Year 11 biology)
In these responses, students have identified at least two components relevant to the question, namely, the direction in which the glucose moves, and the steps involved in this movement.

Category D (Movement towards an end-point) Within these responses, students linked the sequence of events involved in the diffusion of glucose from the capillary and into muscle cells with the cellular requirement for glucose.

As exercise is carried out stores of glucose within the muscle is used, this is replaced by the glucose molecules in the capillaries that diffuse into the muscle cells when stores are low. (Student 18, Year 12 biology)

Essentially, the realisation that glucose is required by cells during exercise provided the stimulus for students to relate the series of steps involved in the diffusion of glucose so as to reach a logical end-point. In other words, the cell's requirement for glucose resulted in the movement of glucose from the capillary into the interstitial fluid and then into muscle cells.

Category E (Initiation of movement: size of molecule or concentrations) The explanations contained within these responses went one step further than those in the previous category in that students provided details as to the factor initiating the movement of glucose. For a number of students this involved the different concentrations of glucose between the capillary and the surrounding cells.

It will move from where there is more glucose to where there is less.

(Student 36, Year 11 biology)

In some responses, also coded into this category, the size of the glucose molecule was recognised as the factor affecting this movement.

An example of such a response is:

the glucose because if is so small is able to move with the blood stream across the cell wall. Moving with corpuscles within the blood, it diffuses through the semi-permeable wall of the capillary into the cells.

(Student 17, Year 12 biology)

Clearly, the size of the glucose molecule, in relation to the semi-permeable membrane of the capillary, is recognised as the major factor affecting its movement. It is interesting to note that while this student has confused the 'cell wall' and 'cell membrane', the use of the term within the context of the explanation suggests an understanding of the overall movement of glucose molecules.

Characteristic of both these types of response, is the change in focus from 'what' is happening in terms of glucose to explaining 'why' glucose moved from the capillary into the body cells. To achieve this end, students identify a single component in their explanations, i.e., concentration differences or the size of the glucose molecule.

Category F (Concentrations; direction of movement specified) Within these responses, students were able to explain the movement of glucose molecules in terms of the concentration gradient. While this factor was implied by some students in the previous category, it became the major focus within this category as students used it to account for the movement of glucose in a particular direction.

The glucose using osmosis again goes through the cell wall. The glucose moves from areas of high concentration (capillary) to areas of low concentration (cell).

(Student 52, Year 11 3-unit science)

Therefore, the explanations in this category identified two components relevant to the movement of glucose from the capillary and into cells. This was discussed within the context of 'why' the movement occurred.

Category G (Equilibrium)

In these responses, students linked together the various components involved in the movement of glucose as identified in the earlier responses. Furthermore, they attempted to complete the 'story' by providing an end-point for the process in terms of an equilibrium.

If the glucose is in higher concentration in the capillary than in the body cells lining it, then the glucose molecules will diffuse across the cell membranes, into the cells, until the concentration of glucose inside the cells is equal to that out side, in the capillary. (Student 1, Year 12 biology)

While the linkages demonstrated in these responses are an overview of the process, students are prepared to close at this point without considering conditions or constraints that may alter their conclusions. For example, the evening out of concentrations as described in this example is an unlikely situation due to the continual cellular metabolism of glucose molecules to produce energy. However, the students at this level have not considered this issue.

Category H (Formal)

In this category of responses, students extend beyond the scope of the question in that they attempted to explain 'why' glucose continued to diffuse from the capillary and into muscle cells.

Glucose is transported down the bloodstream to the places where it is needed. When it reaches its destination it diffuses to the cell and/or the interstitial fluid. This diffusion occurs as the glucose is being used in respiration and therefore there is a lower concentration of glucose molecules in the cells. As molecules diffuse down a concentration gradient then they go from a place with a higher concentration of glucose (the capillary) to a place with a lower concentration of glucose (the cell).

(Student 51, Year 11 3-unit science)

Characteristic of the responses in this category is the ability of students to recognise that the metabolism of glucose by cells to produce energy (i.e., respiration) creates the concentration differences which ultimately drives the movement of glucose molecules into cells. Therefore, these students acknowledge that the attainment of an equilibrium is not the full story in terms of the movement of glucose.

APPLICATION USING THE SOLO TAXONOMY

In terms of the SOLO Taxonomy, each of these categories of responses can be represented within a particular mode and level. Essentially, categories B-G are representative of the concrete symbolic mode in that the world experienced by students is described with increasing sophistication as demonstrated by a sequence of levels of responses. Essentially, categories B-C-D are representative of unistructural, multistructural and relational levels of responses, respectively. Characteristic of this sequence of levels is students' emphasis on the overall or macroscopic view of diffusion in terms of 'what' happens. This is to a large extent perceptual, as students appear to visualise particles moving from one place to another thereby demonstrating the support of the ikonic mode. Furthermore, many of the explanations provided by students were supported by diagrams and practical examples. The responses in categories E-F-G are also indicative of unistructural, multistructural and relational levels of understanding, respectively. There is, however, a change in focus in this sequence of responses as students attempted to address 'why' the movement of glucose occurred. To achieve this end, students identified the component they perceived drove the diffusion of glucose and provided detailed explanations as to its contribution. This required a change in abstraction to a molecular level which was

demonstrated by the replacement of terms, such as ‘particles’ and ‘substances’ in the first cycle, by ‘molecules’ in the second. Responses, therefore, demonstrated a conceptual emphasis rather than a visual one as characterised in the first cycle.

Consequently, the macroscopic and perceptual view furnished by students in the first cycle was replaced by a microscopic and conceptual view in the second cycle of levels. These modes and levels are represented in

Figure 1.

Responses in category H are indicative of the formal mode as students moved away from the concrete referents of the information provided within the question to a higher level of abstraction. This was demonstrated by students’ abilities to recognise energy as the factor driving the process of diffusion thereby incorporating a concept unrelated directly to the context of the question being addressed.

(insert figure 1 near here)

(See http://fehps.une.edu.au/F/s/curric/pg/dPanizzon/h.html)

Question 2

The following diagram illustrates the changes to a red blood corpuscle (RBC) (magnified x400) when transferred from its normal environment(A) and placed into a 15% salt solution(B).

See http://fehps.une.edu.au/F/s/curric/pg/dPanizzon/h.html

EXPLAIN the reason for the changes in the appearance of the plant cell, giving as much detail as possible in your answer.

Seven categories of responses were discerned for this question demonstrating an increasing level of sophistication in the understanding of this question from simple statements regarding the changes in the cell, to detailed accounts describing why the changes occurred.

CATEGORIES OF RESPONSES

Category A (Not codable)

All of the responses in this category were blank and treated as missing data.

Category B (Salt/water caused the changes)
In these responses, students identified either salt or water as the factor initiating the changes in the RBC. For example, some students stated that
the salt did it.
(Student 33, Year 11 biology)

Alternatively, others supplied responses such as

the movement of water out of the cell.
(Student 12, Year 12 biology)

Characteristic of these responses was the identification of a single feature pertinent to the question.

Category C(Salt and effects or water and effects on RBC
In this category, students recognised that the addition of the salt solution (i.e., situation B) had resulted in particular changes in the

RBC which they were able to specify.

Main reason is because of the cell shrinking due to the salt solution.

(Student 20, Year 12 biology)

In contrast, the majority of students focused on the movement of water from the RBC and the resultant effects on the shape of the cell.

Because water has been lost from the cell into the surrounding environment, the cell membrane has shrunk, and eventually broken, releasing the cells cytoplasm.

(Student 9, Year 12 biology)

Although the content of each differs, the emphasis is the same in that either salt or water was identified as the factor initiating movement which led to the changes in the RBC. Therefore, at least two components were characteristic of the explanations coded into this category.

Category D (Salt, water, and the changes in RBC)
The responses in this category contained a number of scientific components that were linked together so as to provide an end-point for the process. In particular, students recognised that the immersion of a RBC into a salt solution caused the movement of water out of the cell which resulted in distinctive changes in the shape and size of the RBC in situation B. For example,
the reason for the change in cell (a) and (b) is that when the salt solution was added, the water moved out of the cell, and the cell collapsed in on top of itself.

(Student 44, Year 11 biology)

In this instance, the student has recognised that the addition of the salt solution initiated the movement of water from the cell. It is interesting to note, however, that a number of the explanations provided by students were not accurate scientifically. For example, one student stated
the reason for the change in appearance, is the addition of the NaCl solution, it replaces the water and the water is drained from the plant. The cytoplasm has collapsed, giving it a shrivelled, smaller appearance.

(Student 46, Year 11 biology)

NaCl as a compound is unlikely to move through the cell membrane as described and if this were to occur it would simply replace the water causing minimal change in the RBC. However, while this student has demonstrated an alternative conception in this regard, a relationship between the salt solution, the movement of water out of the cell, and the subsequent changes in the RBC has been identified.

Category E (Concentrations identified as a reason underlying movement) These explanations went one step further than those in the previous category in that students endeavoured to explain in greater detail, 'why' the changes had occurred in the RBC between situations (A) and (B).

The salt solution entered the cell and because of the changed concentration the cell reacted and shrunk in size and the membrane collapsed.

(Student 8, Year 12 biology)

While the response is not accurate scientifically, the student has attempted to justify the movement in relation to differences in concentrations. In other words, the focus has changed from describing 'what' happened to the cell to explain 'why' it occurred. Within this category, students identified one component in their explanations, i.e. concentration differences.

Category F (Concentrations; direction of movement specified) As with the previous category, students recognised that the movement of substances between the internal and external environment of the RBC was driven by differences in concentrations. However, this was developed further with students addressing the direction in which substances were likely to move and the reason for this.

The fluid inside the cell (of high H2O concentration) has moved to the fluid outside of the cell (which has lower H2O concentration). (Student 39, Year 11 biology)

Demonstrated within this explanation is an understanding that the concentration of water in the solution surrounding the RBC is greater (i.e., higher ratio of solute to water molecules) compared to the solution within the cell (i.e., lower ratio of solute to water molecules)

resulting in water moving from the RBC into the external environment. Therefore, each of the responses contained two components relevant to the question.

Category G (Equilibrium)

Within this category of responses, students recognised that the movement of substances from the internal environment of the RBC to the external environment would not continue indefinitely. Therefore, they were able to provide an end-point for the process.

The reason for the changes is the diffusion of water from inside the cell, to balance the concentrations of solute and solvent. The addition of NaCl has made the concentration of H2O less, on the outside and therefore water comes from the inside to equalise it. (Year 11, 3-unit science)

Characteristic of these responses was the recognition by students of a relationship between the concentration of the salt solution, the movement of water out of the RBC along with the realisation that there was an end-point for this process, i.e., equilibrium.

APPLICATION USING THE SOLO TAXONOMY

In terms of the SOLO Taxonomy, all of the coded responses for this question are representative of the concrete symbolic mode. In addition, it was possible to discern two cycles of levels. In the first, categories B-C-D are indicative of unistructural, multistructural, and relational levels of understanding, while categories E-F-G in the second cycle illustrate unistructural, multistructural, and relational levels, respectively. Characteristic of the first cycle was students' attempts to provide an overview of the problem by addressing 'what' happened from situation A to B. The focus for explanations was macroscopic as students concentrated on the salt solution, water, and the changes to the RBC. Alternatively, within the second cycle, students demonstrated a deeper interest in 'why' the movement of water occurred. In other words, they were concerned with the underlying mechanism driving the water movement and the obvious changes to the RBC thereby changing from a macroscopic to a microscopic focus. These levels are summarised in Figure 2.

(Insert figure 2 near here)

(See http://fehps.une.edu.au/F/s/curric/pg/dPanizzon/h.html)

CONCLUSIONS

The purpose of this research was to investigate students' understandings of diffusion and osmosis using the framework provided by the SOLO model. From the results discussed in this paper, it is possible to identify a pattern of developmental growth for each of these concepts, and, subsequently, support each of the research questions posed at the beginning of this paper.

In terms of SOLO, the majority of students in Years 11 and 12 for both questions produced responses indicative of the concrete symbolic mode. Within this mode, it was possible to discern two cycles of levels. In the first cycle, students focused on addressing 'what' happened in relation to the movement of substances in each instance thereby demonstrating a macroscopic and perceptual view of the processes of diffusion and osmosis. Characteristic of this cycle was the use of terms, such as 'particles' and 'substances', and an interest in the obvious features of the question, such as glucose, salt, water, the capillary, and the RBC. Responses within the second cycle contained explanations as to 'why' substances moved in particular directions, representing a change in emphasis from a macroscopic to a microscopic scale of thinking. Corroborating this notion was the use of the term 'molecules' instead of particles or substances. Clearly, students became more concerned with

explaining the process behind the movement of substances thereby incorporating the concepts of a concentration gradient and equilibrium.

It is possible to discern an overall pattern in the development of understanding within the concrete symbolic mode that is consistent for diffusion and osmosis in terms of the emphases of the two cycles. Furthermore, in relation to the second cycle, the descriptors for both processes are identical with concentration differences, their effect on the direction of movement, and the attainment of an equilibrium distinguishing between the levels of responses.

In terms of differences in these developmental patterns, this appears in relation to the first cycle. Essentially, the descriptors for the responses in this cycle differed in the developmental paths for the two processes. However, this is to be expected given the different contexts and the macroscopic focus demonstrated by students as they concentrate on the salient features provided in the questions. It is interesting to note that once this changes to a microscopic perspective, the two paths converge as outlined earlier. The other difference to emerge is the identification of the formal mode for Q1 involving diffusion but not for Q2 dealing with osmosis. This may relate back to the complexity of the task required of students, or indicate that a larger research sample is required.

Although not a specific issue in the research, a number of alternative conceptions held by students in the areas of diffusion and osmosis emerged from this investigation. While this work requires a deeper analysis, it does appear that the SOLO model provides a structure to explore these alternative conceptions and suggests a framework to both help identify and explain the robustness of such conceptions.

Consequently, the framework provided by the SOLO Taxonomy provides a tool for identifying the growth of students' understandings of scientific concepts. The results discussed in this paper suggest an overall similarity in the developmental pattern for students' understandings of diffusion and osmosis. However, in terms of future research directions, two possibilities arise. Firstly, the incorporation of university science students would test the consistency of these patterns of growth with an older research sample. Secondly, in terms of social and contextual constructivist ideas, it would be interesting to investigate these developmental paths with students in different science courses at a university level. Research is currently being undertaken in both these areas.

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