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Paper Title: **Understanding Cellular Respiration**

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Understanding Cellular Respiration

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This study focused on the problem of cellular respiration for several reasons. First and most importantly, cellular respiration is critical to an understanding of several of the organizing conceptual schemes of the discipline, including energy flow in natural ecosystems and metabolic activities of multicellular organisms such as digestion, respiration, circulation, and excretion. Second, the topic of cellular respiration is taught at the middle school, high school, and university levels and in a wide range of courses and contexts. Third, it is poorly understood by students and judged to be a difficult topic by many teachers (Igelsrud, 1989).

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METHOD

To identify and document the frequencies of scientifically acceptable and alternative explanations a two-phase approach was employed. In the first (constructive) phase, concept maps and clinical interviews were used to explore understandings about cellular respiration held by introductory, college-level biology students (N=52) who had experienced a series of lectures and a laboratory on basic metabolic processes of the cell. Students responses formed the basis of a conceptual inventory which was used in the construction of an open-ended testing instrument. In the second (validation) phase, the instrument was administered to a group of *novice* biology students (N=100) before and after relevant instruction in cellular respiration and to a group of *experienced* biology students (N=100) enrolled in upper-level and graduate courses. Students were completing degree requirements at a regional campus of a state university in southeastern North Carolina.

RESULTS AND DISCUSSION

This report presents the salient findings and analysis of one of the open-ended tasks, **The Mouse and The Plant.** The interviews and concept maps revealed a large number of alternative conceptions about the relationships of cellular respiration and photosynthesis and about the role of plants and animals in natural ecosystems. Many of these problems were recognized much earlier by Wandersee (1983) in an excellent, cross-age study on plant growth and nutrition. Several of these difficulties are illustrated in the following: "Plants undergo cellular respiration but it is different from us. They want carbon dioxide..." "The plant needs carbon dioxide to synthesize energy. Light energy is the source of energy for the plant itself. Plants get food from water and nutrients in the soil." "Plants don't need oxygen. They can get oxygen from the water. [The] mouse doesn't need carbon dioxide because it gets carbons from food." "If there were no plants on Earth, animals would die. If there were no animals, plants would die."

The central conceptual problem seemed to be that plants don't respire, at least not in the way animals do. To probe this issue in depth, several versions of a task which depicted a mouse and plant in a sealed-glass container with adequate amounts of food and water for the mouse and adequate amounts of sunlight and water for the plant were field tested. In the final version of this task, the subjects were confronted with the following illustrated problem: In container A there is a mouse with unlimited food and water. At the time the container is sealed, there is air inside but no more can be added. After awhile the mouse dies. In container B, there is a green plant with unlimited sunlight and water. At the time the container is sealed, there is air inside but no more can be added. Unlike the mouse, the plant lives. Explain why (in detail). This task used a confrontational strategy to force students to resolve some of the inconsistencies in their thinking and to formulate a feasible solution to a basic biological problem.

A panel of experts identified the following set of eight scientifically acceptable propositions that they viewed as central to solving the task: (1) The plant is able to produce its own food through the process of photosynthesis, (2) a process that requires carbon dioxide and water; (3 and 4) The plant is able to use the sugar and oxygen products from photosynthesis in cellular respiration; (5 and 6) It is the process of cellular respiration that produces carbon dioxide and water for photosynthesis, and the process of photosynthesis that produces oxygen and sugar for cellular respiration. (7) Energy from the sun enters the container but other requirements must be cycled, and (8) during the process of cellular respiration ATP is formed. Except for (5) cellular respiration produces carbon dioxide and water, it appears that initial instruction in introductory biology had little effect on student understanding. Subsequent instruction in upper-level courses had a marginally beneficial effect on two other propositions: (3 and 4) The plant is able to use the sugar and oxygen products from photosynthesis in cellular respiration.

For many subjects, the real difficulty in **The Mouse and The Plant** task is to explain how plants obtain carbon dioxide for photosynthesis in a sealed environment. If plants do not respire, what is the source of carbon dioxide? So tenacious is the notion that carbon dioxide must be supplied by an animal, that a 24-year-old male graduate student vented his frustration in the following way: "I do not understand how the plant lived without a source of carbon dioxide for photosynthesis. Surely, it would run out in a sealed container. In all my years in biology (since 7th grade) nobody said anything other than plants get carbon dioxide from the atmosphere."

Subjects found several ingenious ways to reconcile this problem. Many simply denied the requirement of carbon dioxide in photosynthesis such as this 20-year-old female who suggested, "Plants can synthesize glucose, unlike the mouse, without oxygen or carbon dioxide. The only needs the plant has can be fulfilled because of the sunlight and the water." Other subjects tackled the problem by suggesting alternative sources of carbon dioxide such as this 19-year-old female, "The plant engages in photosynthesis, the light reaction of which consumes carbon dioxide and produces oxygen, and the dark reaction consumes oxygen and produces carbon dioxide."

For a large portion of subjects the task proved insolvable; they were ultimately unable to resolve the internal contradictions in their reasoning. In many of these cases the resolution was simply to offer some variation of the dictum, photosynthesis is the plant's form of cellular respiration.

CONCLUSIONS AND IMPLICATIONS

This study began an exploration of the wide range of conceptual difficulties confronted by students who seek to understand the basic processes of cellular respiration; processes that are central to a meaningful appreciation of life at the organismic and community levels of biological organization. Although only the "tip of the iceberg" has been touched, findings justify three general conclusions.

Regardless of ability level, beginning college students harbor an array of alternative conceptions that impede understanding cellular respiration. Many of these problems are inherent in and unique to the life sciences and the emergent nature of knowledge in the discipline. Among the problems students have is a lack of experience in "thinking at the cellular level"; that is, seeking cellular explanations of biological phenomena that manifest themselves at the organismic and community levels of organization whether those phenomena involve, for example, the exchange of gases or the utilization of food. It appears that well-planned instruction may help students shift the locus of their explanations to molecular and cellular levels. Unfortunately, this shift may only be transitory unless provision is made to help students establish meaningful connections among the levels.

Conceptual problems that impede understanding of cellular respiration often persist after instruction and new ones arise in the process. It is clear that instructional practices in common use need rethinking and substantially more emphasis needs to be placed on efforts to help students integrate and reconcile new knowledge within their existing frameworks. Common practices that encourage "compartmentalization" and rote mode learning need careful scrutiny.

Conceptual difficulties that are not addressed in beginning college students remain intact through the undergraduate years despite repeated instruction at successively more advanced levels. The evidence presented here strongly suggests that the understandings students hold at the end of the freshman year are, in many cases, not substantially modified in upper-level courses. For the typical undergraduate student, this means that time devoted to learning about the events of cellular respiration in courses such as cell biology, physiology, and microbiology is not well spent.

In conclusion, we offer are some specific, practical suggestions for those who wish to encourage meaningful learning and understanding in this complex domain. Although this research has only "scratched the surface", these suggestions are supported by the work to date:

Time and Interaction Considerable more time must be allocated to the topic of cellular respiration in the curriculum. That time might be profitably spent in small ("cooperative") group activities including work problem sets, discussions, and interactive, computer-aided instruction. The best evidence suggests that knowledge construction is time-consuming and often painful work that can be facilitated by intense and frequent interaction between the instructor and students of differing abilities (Driver, 1986). For high school and college instructors this means less lecturing and more time spent in one-on-one activities especially in the laboratory where hands-on opportunities can be substituted for "teacher talk".

Sequencing In many curricula, the topic of cellular respiration is introduced relatively early in the course and typically finds a slot somewhere between osmosis and mitotic cell division. To the biologist this placement may appear "logical"; respiration is, after all, a cellular phenomena and belongs with other cellular phenomena. This placement needs rethinking. It is entirely probable that the topics of cellular respiration and photosynthesis are better understood within the context of energy flow in natural ecosystems, following a consideration of important physiological topics such as gas exchange, digestion, and transport mechanisms.

Chunking Often the teaching of cellular respiration is reduced to a sequential presentation of the principal metabolic intermediates, enzymes, and reactions that comprise the glycolytic, citric acid, and electron transport mechanisms. From the vantage point of those concerned with constructing meanings and enhancing understanding, this seems to offer a near-perfect prescription for rote mode learning. To help students avoid this pitfall, we suggest that instruction focus on the larger, more potentially meaningful "chunks" or patterns in the knowledge domain. For example, the sequence of ten major reactions comprising the glycolytic pathway can be reduced to four significant events: a "pump priming" event in which ATP is used to phosphorylate a 6-carbon compound; a "splitting" event in which the phosphorylated 6-carbon compound is hydrolyzed into two 3-carbon compounds; a "redox" event which produces the high-energy compound, NADH; and a "phosphorylation" event which synthesizes ATP. Similar chunking can be accomplished with the major events of the citric acid cycle and electron transport mechanism.

Scope Closely related to the issue of chunking is that of scope; ie. How much can be reasonably "covered in the available time? Take solace in the analogy that likens the curriculum to a wall composed of bricks and mortar. Concepts constitute the "bricks" of the curriculum and relationships the "mortar". Judging by the coverage given to cellular respiration in the most widely adopted secondary and college-level textbooks, it appears that teachers spend far too much time piling up bricks and an insufficient amount of time applying mortar. Can a wall constructed in this manner be expected to stand for any length of time? Students who are given an opportunity to engage in activities such as concept mapping can learn to construct their own "walls of knowledge" in unique and meaningful ways (Wandersee and Novak, 1990).

Anticipating Difficulties As conceptual difficulties are encountered in our students, we have found it helpful to record these problem areas in a format that can be readily accessed and usefully applied in subsequent instruction. A format especially valuable for recording and accessing knowledge about conceptual problems is the "composite concept map". Such a map is constructed entirely from propositional statements offered by students themselves and its value lies in alerting us to and helping us anticipate and recognize conceptual problems that arise in the course of instruction. These composite concept maps are "road maps" that suggest possible avenues of student error and blind alleys that are commonly traversed in the solution to a problem.

Models and Analogies There is substantial evidence that instruction designed to help students build mental models through the use of analogies can be very effective, especially when the domain is comprised of abstract objects or events that are difficult to visualize such as those of cellular respiration (Clement, 1987). As an example, the chemiosmotic mechanism used to establish an electrochemical gradient across the inner mitochondrial membrane is often difficult for students to visualize. The potential energy stored in this gradient can be likened to the energy stored in a balloon filled with helium. Analogies such as this can serve as, vehicles for introducing interesting and memorable classroom demonstrations.

Evaluation In discussions among ourselves and with other classroom teachers we have come to accept, with some regret, the old dictum that "evaluation drives learning." With this in mind, it seems unrealistic to expect students to engage in any real effort to understand complex topics like cellular respiration unless our evaluation methods encourage meaningful learning. For several years, we have experimented with a variety of "authentic" evaluation tools and have come to rely heavily on a combination of writing and concept mapping in our introductory biology courses (Arnaudin, Mintzes, Dunn and Shafer, 1985; Wallace, Mintzes and Markham, 1993).

Applications For many students the value of a learning experience can be best measured in its applicability to their daily lives. There is a strong motivational pay-off in classroom and laboratory activities such as wine and yogurt making to illustrate some of the principles of the fermentation process. Students have engaged in jogging exercises and the Harvard "step test" to illustrate the relationship of breathing and circulation in cellular respiration. Measuring the metabolic rates of a mouse and/or frog in a simple metabolism chamber can provide an opportunity to help students relate gas exchange and cellular respiration. In summary, cellular respiration is too important to be relegated to the textbook and the chalkboard. Students must be engaged in active meaning making (Novak, 1987) if understanding is the goal.

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