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De-black-boxing Learners: What is Occurring in their Minds When they Answer Multiple-choice Questions that Assess their Understanding of Biological Concepts?

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ABSTRACT

Many biology textbooks and test banks accompanying these textbooks have begun to classify multiple-choice questions (MCQs) according to Bloom's taxonomy. Teachers, however, encounter significant difficulties in adjusting their assessment practices to the low performance of students and in helping them enhance their respective cognitive skills because the mental processes that Bloom's categories indicate are captured from the perspective of learners' mental behaviour or observable learning outcomes; learners are treated more as black boxes and less as input-state-output subjects, as constructivist learning theories suggest. Thus, interior mental facts and processes occurring in their minds remain unexplored. The purpose of the present paper is to open learners' black boxes and reveal the specific mental facts and processes occurring in their cognitive structures when answering Bloom's classified MCQs, whose subject matter content concerns biological concepts. To accomplish this purpose, we associate knowledge drawn from the philosophy of biology with the conceptual nature of Bloom's lower-level categories such as 'knowledge' and 'comprehension'. This knowledge involves types of statements and arguments that can be found in scientific language, along with different and interrelated aspects of biological concepts that learners should know if they are to understand declarative knowledge. The implications of our epistemological analysis for the nature of MCQ distractors and the notion of misconceptions will also be discussed.

Keywords: Bloom's Taxonomy, misconceptions, multiple-choice questions, nature of science, philosophy of science

INTRODUCTION

With increasing emphasis on online assessment, the spotlight has returned to the question of multiple-choice questions (MCQs). Remarkably, not only online assessment but also many biology textbooks and test banks accompanying these textbooks (e.g., Barstow et al., 2008; Hoefnagels, 2015; Mader & Windelspecht, 2017; Raven et al., 2017; Reece et al., 2014) have begun to classify MCQs according to the complexity of the mental skills required for answering each question.

The classification scheme they use is based on Bloom's (1956) taxonomy and involves lower-level cognitive categories such as 'knowledge' and 'comprehension', higher-level cognitive categories such as 'analysis', 'synthesis' and 'evaluation' and transitive categories between the two extremes such as 'application' (Crowe et

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al., 2008; Krathwohl, 2002). 'Knowledge' is a mental skill addressing factual knowledge and indicates the ability of students to retrieve previously learned material from their memory; 'comprehension' indicates the ability of students to capture conceptual knowledge (i.e., the interrelationships among the elements within a larger scientific structure that enable them to function together); 'application' is the ability of learners to use learned material in new situations and predict the most likely outcome given these situations; 'analysis' is the ability to break a whole into its component parts and find the relationships among these parts; 'synthesis' is the ability to integrate separate concepts or ideas and form new wholes; and 'evaluation' is the ability to present and defend opinions about scientific information and the validity of scientific ideas based on a set of criteria.

Many students come to educational settings with the assumption that science consists of only a great deal of memorization, and instructors often ensure this assumption when they use a high percentage of lower-order or knowledge-style MCQs in the assessment phase of their teaching. However, science learning is something more than facts and memorization; thus, many scholars suggest a shift from the high percentage of lower-order MCQs towards a proper balance between lower- and higher-ordered questions. This insight has been instantiated in several empirical studies in which Bloom's taxonomy, associated with various assessment methods, has been employed in designing tools (Athanassiou et al., 2003; Crowe et al., 2008) and rubrics (Bissel & Lemons, 2006) for assessing learner performance. The results are encouraging because they demonstrate that students enhance their mastery of the teaching material and strengthen self-responsible learning behaviour, whereas instructors create pedagogical transparency and promote student metacognition.

Nonetheless, given that MCQs are gradually advancing to the status of the most practical assessment method (Crowe et al., 2008), there is significant need for developing more-efficient associations of MCQs with Bloom's taxonomy. This need is not only induced by the difficulties that teachers encounter in classifying MCQs into Bloom's taxonomy categories (Barstow et al., 2008) and accurately identifying the Bloom's cognitive levels with which students struggle (Kocakaya & Kotluk, 2016). Teachers also encounter significant difficulties in adjusting their teaching practices to the low performance of students and in helping them to enhance their respective cognitive skills.

More specifically, although Bloom's categories indicate mental processes, these processes are captured from the perspective of mental behaviour or observable learning outcomes that are grounded on learning objectives defined in terms of some subject matter content and what is to be done with that content (Krathwohl, 2002). For example, behavioural verbs such as 'define', 'list', 'state', 'name', 'identify', 'define' and 'show' are the only coding criteria for classifying MCQs and learners' assessment performance into the category of 'knowledge', whereas the analogous verbs concerning 'comprehension' are 'restate', 'paraphrase', 'explain', 'describe', 'illustrate', 'contrast', 'compare' and 'categorize' (Allen & Tanner, 2002). Thus, the current combination of Bloom's taxonomy categories with MCQs in assessing learners' declarative knowledge including the clustering of MCQs in rubrics formed by these categories (a) favours the treatment of learners as black boxes or input-output 'subjects' whose performance (outputs) depends upon their observable responses to particular stimuli (inputs); learners are not treated as input-state-output subjects as constructivist learning theories suggest, and interior mental facts and processes occurring in their minds remain unexplored, (b) disregards the fact that each specific Bloom category (e.g. 'knowledge', 'comprehension', 'application', etc.) represents a variety of qualities that can differ from MCQ to MCQ and, (c) results in coarse-grained assessment planning that is inefficient for unravelling differences among learners or among MCQs classified into the same category and informing beneficial instructional interventions. For example, if a student has a low score on MCQs classified as 'application', then what is the proper instructional intervention? Should this student address a large number of MCQs classified as 'application' until his/her score is raised? Moreover, if there are no questions or question sequences including follow-up questions informed by the specific mental facts and processes occurring in the learner's mind, then how can formative assessment objectives be achieved? How could teachers interact with students and help them cope with their conceptual inadequacies or deficiencies?

The purpose of this paper is to open learners' black-boxes and reveal the specific mental facts and processes occurring in their cognitive structures when they attempt to answer Bloom's classified MCQs whose subject matter content concerns biological concepts. To accomplish this purpose, we will associate knowledge drawn from the philosophy of biology with the conceptual nature of Bloom's categories. Certainly, exploring the heuristic potential of the philosophy of biology in opening learners' black-boxes is not an easy task. Numerous theoretical and empirical studies focussing on different Bloom categories and different aspects of the same category are needed. Thus, as part of a larger project, the present essay takes an initial step towards this exploration by largely focussing on Bloom's lower-level categories such as 'knowledge' and 'comprehension'.

These categories were chosen as the research topic because, due to the hierarchical structure of Bloom's taxonomy (Allen & Tanner, 2002), they are considered significant prerequisites for learners to capture Bloom's higher-level cognitive skills.

Research Questions

Prior to embarking on our investigation, let us consider examples of MCQs that aim at assessing students' understanding of biological concepts.

Example 1. (Barstow et al., 2008, p. 1). A localized group of organisms that belong to the same species is called a

A) biosystem
B) community
C) population
D) ecosystem
E) family

Correct Answer: C

Skill: Knowledge

Example 2. Competition is an interaction

A) in which individual organisms suffer a reduction in fecundity, growth or survivorship
B) in which individual organisms have negative effects upon each other by influencing access to resources
C) that occurs among competitors
D) different from predation, commensalism and amensalism

Correct Answer: B

Skill: Knowledge

Example 3. Homeostasis is the ability of organisms to

A) maintain their temperature constant despite temperature changes in their external environment
B) alter their internal environment appropriately when external conditions change
C) maintain their internal environment constant despite external environmental changes
D) change their external environment

Correct Answer: C

Skill: Knowledge

The question arising is what occurs in students' cognitive structures when they attempt to answer the previously mentioned MCQs. A possible answer is that students retrieve the scientific definitions of the concepts "population", "competition" and "homeostasis" from their memories and allocate them across the choices given. However, are these questions identical with respect to their assessment status? Do the questions only assess the ability of students to recall definitions?

In addition, consider the following MCQs:

Example 4. Which of the following is not an infectious disease?

A) flu
B) syphilis
C) diabetes
D) the common cold

Correct Answer: C

Skill: Comprehension

Example 5. (Barstow et al. 2008, p. 1). All of the organisms on your campus make up

A) an ecosystem
B) a community
C) a population
D) an experimental group
E) a taxonomic domain

Correct Answer: B

Skill: Comprehension

Example 6. Which levels of ecological organization are depicted in the images shown in **Figure 1**?

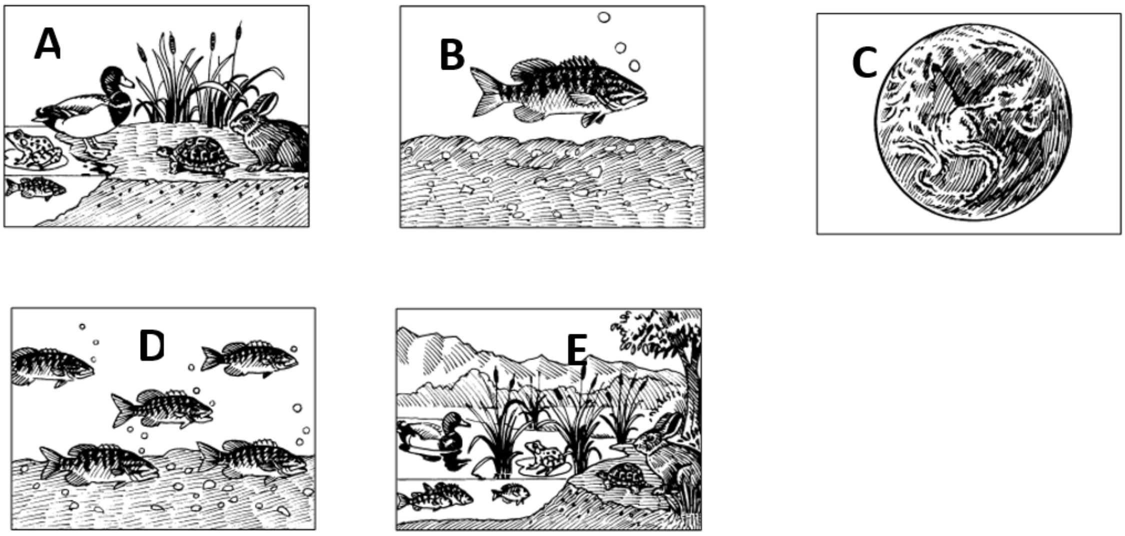

Figure 1. Image reprinted from Holt et al., p. 96

A) A: ecosystem, B: organism, C: biosphere, D: population, E: biological community
B) A: biological community, B: organism, C: biosphere, D: population, E: ecosystem
C) A: population, B: organism, C: biosphere, D: biological community, E: ecosystem
D) A: biological community, B: organism, C: ecosystem, D: population, E: biosphere

Correct Answer: B

Skill: Comprehension

MCQs 4, 5 and 6 appear different from MCQs 1, 2 and 3. They ask students not only to recall definitions but also to find objects or examples in the real world to which such definitions apply. Thus, according to Bloom's taxonomy, they assess the higher-than-'knowledge' skill of 'comprehension'. However, are these questions identical with respect to their assessment status? What mental processes are occurring in students' minds when they attempt to answer these questions? Are these processes similar? What problems appear in their cognitive structures when answering these questions erroneously? Are these problems of the same type?

Before discussing these research questions, it is crucial to focus on the logic of scientific language. Scientific language underpins learners' declarative knowledge, and its logic determines how students reason. Students' reasoning employs arguments consisting of statements as building blocks, which in turn contain concepts as building blocks. Thus, our investigation into the mental facts and processes occurring in students' cognitive structures when they attempt to answer MCQs whose subject matter content concerns biological concepts cannot but be based on insights drawn from conducting epistemological analysis on three levels of scientific language: a) on statements as they are expressed by sentences; b) on arguments, that is, statements combined in patterns of reasoning; and c) on concepts as they are expressed by words.

Accordingly, the present essay is structured as follows: The first section describes the theoretical framework that we followed in analysing MCQs. It highlights the types of statements and arguments that can be found in scientific language and also clarifies different and interrelated aspects of biological concepts from a primarily normative epistemological standpoint, focussing on what students should know if they are to understand biological concepts. The second section employs the epistemological knowledge offered by the previous sections to analyse the mental facts and processes occurring in students' cognitive structures when they attempt to answer specific MCQs. In the light of this discussion, the implications of our epistemological analysis for the nature of MCQS distractors and the notion of misconception will also be examined.

THEORETICAL FRAMEWORK

Scientific Statements and Arguments

From the perspective of logic, the statements that compose scientific language are cognitive. Cognitive statements are statements that are true or false and can be distinguished from other statements that are not true or false, such as normative statements (Van der Steen, 2001). Normative statements express norms or values and can be considered acceptable or unacceptable.

Cognitive statements are divided into empirical and logical statements (Van der Steen, 1993). A statement is empirical if its truth or falsity depends upon how it presents facts. In science and philosophy, the concept of 'fact' is considered a particularity and references situations or events that occur at particular times and places (Sattler, 1986). For example, the statement that 'tourist activities disturb the habitat of *Caretta caretta* turtles in the Laganas gulf of Zakynthos (Greece)' is an empirical statement. It expresses a multitude of facts rather than only one, and its truth or falsity depends upon the results of empirical research.

Logical statements, such as "1 + 2 = 3" and "competition is an interaction in which individual organisms have negative effects upon each other by influencing access to resources", differ from the previous empirical statements (Van der Steen, 1993). They have no empirical content because they are not working with facts; their truth or falsity depends upon how they handle symbols ("1", "2". "+", "=", and "3") or linguistic meanings. Thus, one need not perform empirical research to decide whether the aforementioned statement about competition is true or false. This statement indicates how 'competition' is defined, and it is true not only due to how the scientific community has achieved a consensus in defining 'competition' but also because it satisfies the so-called 'definition rules' (Van der Steen, 1993). For example, a) it is not a broad definition; it does not apply to more ecological relationships than those described as competitive by biologists (e.g., the definition 'competition' as 'an interaction in which individual organisms suffer a reduction in fecundity, growth or survivorship' also refers to prey-predator relationships), b) it is not a circular definition; it does not contain words which are themselves defined with the unknown word which is to be clarified (e.g., "competition is an interaction which occurs among competitors") and c) it is not unnecessarily negative; it does not refer to features that are absent rather than present (e.g., 'competition' is 'an interaction, different from predation, commensalism and amensalism').

Logical statements are not independent from empirical statements. Logical matters concerning the use of scientific language affect the formulation or evaluation of empirical statements. For example, the empirical statement that "tourist activities disturb the habitat of *Caretta caretta* turtles in the Laganas gulf of Zakynthos" presupposes the use of logical statements, such as the definition of 'disturbance', and their truth or falsity depends upon how 'disturbance' is defined. Under one interpretation of 'disturbance', this empirical statement might be true but under a different interpretation might be false. Hence, before addressing the truth or falsity of empirical statements, someone must consider questions of meaning that are inextricably involved in empirical matters. In other words, facts are never free from theoretical implications, or as **N**ature **O**f **S**cience (NOS) researchers hold, observation is theory laden (Lederman et al., 2002).

Moreover, logical and empirical statements, considered building blocks of scientific language, are not isolated but combined in patterns of reasoning called arguments. Scientific arguments represent the inference of a particular statement referred to as a 'conclusion' from other statements referred to as 'premises' and can be classified into deductive and inductive (Van der Steen, 1993). Inductive arguments are arguments in which the premises are assumed to make the conclusion probable. In contrast, deductive arguments are patterns of reasoning in which the premises are assumed to make the conclusion inevitable; the conclusion cannot be false when the premises are true. Note that an important distinction of deductive arguments is between valid and invalid or fallacious arguments on the one hand and between true and false arguments on the other hand. Deductive arguments are valid when they have a proper logical form such as modus ponens[1] or modus tollens and true when this proper logical form applies to premises that are not false.

With respect to school science, logical and empirical statements can be found in every scientific school textbook. Thus, what teachers ask students to do when they teach the content knowledge of scientific school textbooks is to learn logical and empirical statements and relate them in forms of reasoning that contain deductive and inductive arguments. However, how are these statements and their logical relationships (arguments) related to the understanding of scientific concepts? Ultimately, how can these two levels of scientific language help us analyse what is occurring in learners' minds when they answer MCQs that assess declarative knowledge?

We now introduce a theoretical scheme that focuses on another level of scientific language, namely, the level of concepts. This theoretical scheme was developed in previously published studies of my own and my colleagues (Schizas & Stamou, 2011, Schizas et al., 2013) and addresses the complexity of learners' understanding with respect to biological concepts. More accurately, this scheme clarifies different and interrelated aspects of biological concepts from an epistemological and normative standpoint that, in a broad sense, focuses on what students should know if the claim that they understand particular biological concepts is to be justified.

Theoretical Scheme: Biological Concepts

Biological concepts come in different types. They can represent things, properties of things, or relationships among things. However, independent of what they represent, they share common epistemological characteristics that are indicated by a four-dimensional theoretical scheme.

The first dimension concerns the 'intension' of concepts. The 'intensional meaning' or 'intension' of a concept consists of qualities or attributes that this concept connotes (Hurley, 2015) and refers to features that belong to its definition, namely, 'defining features' (Van der Steen, 1993). Thus, being an interaction among organisms (i), with negative effects and (ii) via resources, are defining features of the concept of competition and connote the type of attributes something must have to be denoted by this term.

The second dimension concerns the 'extension' of concepts. The 'extensional meaning' or 'extension' of a concept refers to its applicability and consists of the members of the class that this concept denotes (Hurley, 2015).

Extension can be further subdivided into 'empirical reference' and 'operationality' (Van der Steen, 1993). A concept has empirical reference if there are concrete things to which it applies. For example, the concept of 'living' applies to 'plants', 'animals', 'microbes', and 'eggs'. Furthermore, a concept is operational in the sense that there are meaning criteria for decisions concerning applicability in concrete cases. Such meaning criteria determine of what the empirical reference consists and include defining features of the concept that help someone decide on reasonable grounds whether this concept applies to particular things. For example, defining features of the concept of 'living' such as movement, growth, sensitivity and reproduction helps us decide whether a particular thing is living.

The 'operational features' of concepts are often accessible to direct observation or direct experimental assessment. However, in many circumstances, the operational features of a concept are not accessible to observation, but their presence or absence can be inferred indirectly (Van der Steen, 1993). For example, it is difficult for someone to directly observe whether something 'respires', which is another meaning criterion to decide whether this something is living. The presence or absence of this attribute, however, can be inferred. Living things need energy to move, grow, respond to stimuli and reproduce, and they take this energy through the respiration process. Note that not only the defining but also the accompanying features of a concept can serve as the meaning criteria for decisions concerning applicability in concrete cases. Such accompanying features are associated with the defining ones but refer to features that do not belong to the intension of the concept. For example, 'evolution' can be viewed as an accompanying feature of life that can help us decide whether a virus is living.

The third dimension concerns the holistic nature of scientific concepts. Scientific concepts are not isolated from each other, and their meaning depends upon the intensional and extensional meaning of a set of concepts that belong to the definitional domain of the concept in question. Thus, the understanding of a particular concept presupposes not only knowledge of its own intensional and extensional meaning but also knowledge of the intentional and extensional meaning of all of these interrelated concepts. All of these concepts have their own definitional domain, and their meaning depends upon the intentional and extensional meaning of other concepts, which in turn have their own definitional domain, and their meaning depends upon for example the meaning of other concepts.

The meaning of concepts is open not only downwards but also upwards. The intensional and extensional meaning of a particular scientific concept is embedded within wider conceptual networks whose structure reflects the structure of the scientific fields or paradigms to which this concept belongs. These structures establish conceptual relationships between the concept in question and other concepts and determine the 'systemic component' of a concept's meaning (Baltas, 1991). For example, the concept of 'decomposition' belongs to the conceptual network of the systems ecology field and, along with its defining features, carries a breadth of accompanying features associated with the concepts of ‘feeding relationships’, ‘food webs’, ‘respiration’, and ‘biochemical cycles’ (Schizas et al., 2013).

The fourth dimension is closely related to this systemic component of a concept’s meaning and involves metaphysical-ontological, epistemological, and methodological assumptions. These assumptions underlie how the concept in question is defined within the scientific field to which it belongs and dictate the latent conditions under which the concept’s manifest meaning makes sense (Baltas, 1986; Schizas, 2012). Additionally, these background assumptions address the transformation of pre-scientific empirical objects into scientific objects along with the elaboration of these latter objects, thereby developing the scientific field to which these objects belong (Stamou, 2012). Throughout this productive process (Baltas, 1986, 2007), these assumptions a) anticipate scientific practice by providing a priori answers to a multitude of ontological, methodological, epistemological and ultimately philosophical issues, such as what is causality, what is wholeness, and how wholeness can be studied; b) articulate the component elements of a given field into a coherent and thus understandable whole; and c) impose certain choices on scientists working in a specific scientific field to observe the empirical world and reconstruct this world in the form of a scientific research object.

This component of a concept’s meaning indicates that a scientific term connotes the attributes that occur in the minds of the scientists who invented this term or use it and primarily refers to the worldview within which the conceptual network of the scientific field to which the concept belongs becomes comprehensible. With respect to a majority of biological concepts, this worldview is no other than the Neo-Darwinian worldview (Schizas et al., 2016). The Neo-Darwinian worldview originates from Neo-Darwinian synthesis and draws its assumptions from the product of this synthesis, namely, evolutionary biology (Smocovitis, 1992; Stamou, 1998). Evolutionary biology is considered a science distinct from the generally narrow-physics based model of science, and it is based in the techniques of hermeneutics and historical sciences (Schizas et al., 2016).

Learners understand the meaning of a particular scientific concept if they have an appropriate understanding of all of these dimensions. However, the third dimension complicates the conditions under which a concept might become comprehensible within educational settings because it calls on us to focus on sets of concepts composing scientific theories or models. This research choice is out of the scope of the present paper. To avoid complexity, we will focus primarily on the first two dimensions of the theoretical scheme presented in this section and only partially on the fourth one because of its strong association with the third dimension. Remarkably, the focus on this latter dimension will help us elaborate on the choice of MCQ distractors and discuss intriguing matters concerning the notion of misconceptions.

DE BLACK-BOXING LEARNERS

To investigate the mental facts that occur in learners’ minds when they attempt to answer MCQs whose subject content matter is biological concepts, we will attempt to associate the dimensions of the above-discussed theoretical scheme with the type of scientific statements and arguments that can be found in scientific language. However, prior to proceeding with such investigation, it is necessary to briefly mention a theme that should always be considered in the analysis of students’ cognitive structures. The scientific language that students use when they try to answer MCQs seldom exhibits its logic explicitly, and the same holds true for the mental facts and processes that occur in the students’ cognitive structures. Thus, to understand what is occurring in these cognitive structures, a type of reconstruction will be performed.

Let us start with MCQs 1, 2 and 3. As mentioned previously, these questions ask students to recognize the definitions of ‘community’, ‘competition’ and ‘homeostasis’ in the choices given. Thus, they assess whether students know the intension of these concepts. Moreover, as discussed earlier, the intension of concepts is predominantly associated with logical statements. Therefore, when students attempt to answer the above questions, they should recall logical statements and identify them in the choices given.

The assessment of this mental process is foremost an assessment of the students’ ability to memorize. However, MCQs 1, 2 and 3 are not completely identical. With respect to MCQ 1, students might recall more than one logical statement (e.g., the definitions of ‘biosystem’, ‘population’, ‘ecosystem’ and ‘family’) and compare all of these statements with the phrase ‘a localized group of organisms that belong to the same species’, which is also a logical statement. Therefore, this question assesses the students’ ability to compare different logical statements although in a frame overarched by their ability to memorize.

With respect to MCQ 2 and 3, students must recall only one logical statement for each question, i.e., the definitions of ‘competition’ and ‘homeostasis’. Apart from that, however, students must avoid distractors. Thus,

Table 1. Deductive argument of the form modus ponens

Premise 1	If a disease is caused by pathogenic microorganisms, then it is infectious
Premise 2	The disease of flu is caused by pathogenic microorganisms
Conclusion	The disease of flu is infectious

with respect to MCQ 2, they should be able to apply certain definition rules to distractors A, C and D to explain why they are erroneous. This question therefore also assesses whether students are familiar with epistemological aspects of logical statements or NOS aspects such as the criteria that definitions should satisfy to be logically correct. Moreover, with respect to MCQ 3, students should possess certain **N**ature **O**f **T**he Sciences (NOTSs; Schizas et al., 2016) views to avoid distractor A. They should know that the concrete empirical phenomena biology grasps and handles using scientific concepts are not simple representations of the relevant general phenomena. Thus, biological generalities (e.g., that organisms maintain their temperature constant) concerning the application domain of biological concepts are contingent because they result from historical/evolutionary processes.

When the informed definitions involved in MCQs 1, 2, and 3 do not presuppose a type of restatement by students, all of these MCQs can be classified at the lowest level of the Bloom's scale referred to as knowledge. However, this classification is not correct for all MCQs that assess students' understanding of biological concepts' intension. Consider the following example:

Example 7. Sequence the following concepts so that each is included in its following concept: a) population b) ecosystem c) organism d) biological community

A. a, b, c, d
B. c, a, b, d
C. c, a, d, b
D. c, b, a, d

Correct Answer: C

Skill: Comprehension

Apparently, this question assesses aspects of the concept's 'population', 'ecosystem', 'organism' and 'biological community', which are primarily related to their intension. Students must recall the definitions of all of these concepts, but doing so is insufficient to recognize the correct answer. Because concepts are linked with classification (e.g., in our case, classification contains four classes), question 7 also asks students to place all of these logical statements (i.e., definitions) in a logical order. Thus, question 7 assesses not only the ability of students to memorize but also their ability to organize previously learned information to acquire an ordered memory. This ability can be classified as 'comprehension' (Duron et al., 2006), which is a higher-level skill than that of knowledge.

Questions 4, 5 and 6 differ from the previous ones because they focus on the extension or reference of biological concepts. The knowledge or understanding of concepts' intention is a necessary but not sufficient condition for the knowledge or understanding of the concepts' extension. This entails that the mental processes occurring in the cognitive structure of students who attempt to answer such questions are expected to be more complex than those occurring in the previous cases. However, there are also important differences among these questions. Let us explain.

Question 4 assesses whether students can apply the concept "infectious disease" to concrete diseases. Initially, students must remember more than one definition to lead themselves to the correct answer. For example, to decide whether the flu is an infectious disease, students must recall two definitions in their memory: the definition of 'infectious disease' (e.g., disease caused by pathogenic microorganisms) and the definition of 'flu' (e.g., acute respiratory illness with high transmissibility caused by viruses). However, their final decision on whether the flu is an infectious disease requires the logical connection of these two logical statements. Apparently, analogous remarks could be made in the cases of the answers B, C, and D. Question 4 displays greater complexity than do the previous ones because it requires students not only to recall isolated logical statements but also to connect them through deductive arguments such as the modus ponens argument described in Table 1. Although the connection of logical statements requires of students the ability to make valid and true arguments, this type of MCQ largely assesses their ability to memorize.

Question 5 also focuses on the extension of biological concepts and thus assesses students' ability to apply concepts to concrete things. However, unlike question 4, question 5 asks students to relate logical statements

Table 2. Deductive arguments of the form modus ponens

Premise 1	If something consists of organisms that share similar morphological features, then they belong to the same species.
Premise 2	In this image, I observe 5 similar morphologically fish.
Conclusion 1	The fish of the image belong to the same species.
Premise 3	If something consists of organisms of the same species living in an area, then this something is a population.
Premise 4 (involves Conclusion 1)	The fish of the image belong to the same species and live in the same area (lake).
Final Conclusion	The fish of the image compose a population

with empirical statements. Students are assessed on their ability to recall definitions and connect these logical statements with the empirical statement '[a]ll the organisms on your campus make up'. Students are assessed not only in terms of their ability to memorize but also with respect to whether they can apply biological concepts to the empirical world. Thus, such questions make the student more extroverted and comply with constructivist learning models, which highlight the experience of students and make it the cornerstone of their learning (e.g., Driver, 1989).

This consistency between MCQs and constructivist learning models is more evident in question 6. This question examines students' ability to identify the extension of concepts such as 'organism', 'population', 'biological community' and 'ecosystem'. Students are asked to remember all of these definitions and apply them to the images they observe. They are assessed on their ability to bind logical statements such as the abovementioned definitions with empirical statements such as "This is a fish" or "In this image, I observe 5 morphologically similar fish living in a lake" by means of two interrelated deductive arguments such as those shown in Table 2. However, note that there are differences between question 5 and question 6 that bring the latter question closer to constructivist learning models. These differences are the following: first, students are asked to do something, for example, to carefully observe images found in the immediate world of their experience and construct their own empirical statements. Thus, consistent with constructivist leaning guidelines, students are asked to become not only more extroverted but also more active. Second, this question assesses students' skills (e.g., observation) that are related to 'procedural' knowledge, whose importance is increasingly emerging in the frame of constructive learning models (e.g., Millar et al., 1994).

MCQs in the form of questions 5 and 6 are increasingly frequent in international biology textbooks because of the strong influence of constructive learning models on how teachable scientific knowledge should be transformed into taught scientific knowledge. These MCQs focus on the relationship between the conceptual and the empirical world and increasingly assess the ability of students to bind logical and empirical statements.

Selecting MCQ Distractors

The four-dimensional theoretical scheme already described can help science educators and teaching personnel choose the type of misconceptions that can be used as MCQ distractors. These distractors can be related to a lack of understanding of features belonging to the definition of the taught concept or stem from ambiguities related to the concept's applicability. These latter can be further subdivided into misconceptions concerning a concept's 'empirical reference' and 'operationality'. The former misconceptions refer to misconceived views of the concrete things to which the concept applies, whereas the latter misconceptions include erroneous meaning criteria for decisions concerning the concept's applicability in concrete cases.

Consider for example the following MCQs:

Example 8. Decomposition is

A) the process through which dead organic matter decomposes by itself and disappears
B) the process through which dead organic matter is softened by wind and rain and is then dissolved in soil
C) the process through which dead organic matter is "getting older" and breaks into small pieces that are difficult to observe
D) none of the above is correct

Correct Answer: D

Skill: Comprehension

Example 9. Which of the following things could not be considered living?

A) grass
B) seed
C) egg
D) mitochondria

Correct Answer: D

Skill: Comprehension

Example 10. (Barstow et al., 2008, p. 1123). Which of the following is an example of an ecosystem?

A) All of the brook trout in a 500 hectare[2] river drainage system
B) The plants, animals, and decomposers that inhabit an alpine meadow
C) A pond and all of the plant and animal species that live in it
D) The intricate interactions of the various plant and animal species on a savanna during a drought
E) Interactions between all of the organisms and their physical environment in a tropical rain forest

Correct Answer: E

Skill: Knowledge

With respect to question 8, the distractors A, B, and C refer to students' misunderstandings of decomposition stemming from how they interpret the world of their experience (Schizas et al., 2013). This question checks whether students' cognitive structures contain empirical statements that prevent the proper understanding of logical statements (i.e., the scientific definition of decomposition).

Misconceptions are related not only to the intension of biological concepts but also to their extension as indicated in question 9. This epistemological distinction between intension and extension can be useful in classifying misconceptions and clustering MCQs into coherent assessment tools. However, the resulting classificatory scheme is not always straightforward. For instance, although question 10 focuses on the extension of the concept of 'ecosystem' because it asks students to provide an example of an ecosystem, a more careful examination of the distractors A, B, C, and D and the correct answer E indicates that students must identify a logical statement (i.e., the definition of ecosystem) in the choices provided. Therefore, question 10 focusses more on the intension of the concept of ecosystem and less on its extension. This focus occurs because the extension of some biological concepts including ecosystem is obscure (Schizas, 2012; Schizas et al., 2018).

Another possible source of misconceptions and MCQ distractors concerns the 'systemic component' of the concept's meaning. Each scientific concept has a particular position within a specific conceptual structure and acquires a particular meaning throughout its relationships to other scientific concepts composing this structure. However, elaborating on this holistic component is out of the scope of our research, and more work must be done in examining misconceptions that arise from how learners understand these relationships. Noticeably, this work focuses on groups of scientific concepts and is expected to illuminate what occurs in learners' minds when they answer MCQs classified into higher-order Bloom categories.

Finally, misconceptions can be causally associated with misunderstandings of the peculiar ontological, epistemological and methodological assumptions that underlie discipline-specific epistemologies and, in particular, the conceptual networks in which the taught scientific concepts are embedded. These misconceptions are difficult to treat, because the underlying background assumptions provide the lenses through which learners should view scientific objects and frame their perceptions.

Consider the following example:

Example 11. John visits a cardiologist for a check-up, and the cardiologist places him on a gym track to obtain the measurements he wants. Among other things, the cardiologist measures John's temperature. Before running on the gym track, his temperature is 36.6 ° C. After running, his temperature is again 36.6 ° C. Based on this passage, please answer the following question:

The temperature of John did not change because

A. John is not sick.
B. physical exercise does not cause fever.
C. when we do physical exercise, our temperature never changes.
D. the function of his body prevented the body temperature increase that physical exercise causes.

Correct Answer: D

Skill: Comprehension

This question examines the 'operationality' of the concept of homeostasis. Learners must recall logical statements pertaining to the definition of 'homeostasis' and primarily use appropriate meaning criteria to decide whether this concept can apply to the particular case described in the MCQ. These criteria (e.g., that a biological variable tends to change but due to homeostasis is maintained constant) are contextually embedded because they belong to a framework overarched by Neo-Darwinian background assumptions. Thus, learners should avoid distractors A and B, which reflect an essentialist and rather Newtonian perspective on viewing biological entities; biological entities do not simply 'are' possessing stable properties but they 'exist' and their properties depend upon internal processes that have been generated during biological evolution (Schizas et. al, 2016). Moreover, learners should avoid distractor C, which reflects inappropriate reasoning on explaining biological phenomena. This reasoning (i.e., if A occurs, then B always follows) is based on the deductive-nomological model and complies with Newtonian types of explanations grounded on universal and non-contextual generalities (Schizas & Psillos, 2019).

Conclusions and Afterthoughts

The assessment of learners' understanding of scientific concepts is an important phase of the instruction process (Bird, 2014). Its successful implementation, particularly in the frame of formative assessment, requires a rational design based more on what occurs in learners' minds and less on the treatment of learners as black boxes or simply input-output 'objects' whose successful assessment performance (outputs) suffices for determining successful instructions (inputs). The former is consistent with constructivist learning theory, whereas the latter is consistent with empiricism and advances the principles of behaviourism to the status of appropriate learning conditions for implementing successful teaching interventions. Remarkably, whereas the conjunction of MCQs with Bloom's taxonomy rationalizes the assessment process, this rationalization usually implies a rather behavioural strategy in planning teachers' assessment interventions; it envisages a trial and error procedure that disregards the mental states of learners.

Constructivist learning models consider students open learning systems or input-state-output 'subjects' and require instructors to know more about their states. The philosophy of science can help proceed in this direction. Using insights from this domain, the present paper elaborates on the mental facts and processes occurring in learners' cognitive structures when they are called on to answer MCQs, whose subject matter content is biological concepts and that measure learners' cognitive skills such as 'knowledge' and 'comprehension'. Although further research on higher-ordered Bloom categories is needed, the present paper can be considered a starting point in providing science educators with a methodology for addressing an in-depth analysis of Bloom's categories. This methodology can help teachers recognize conceptual 'symptoms' or problems behind learners' erroneous answers to MCQs, thereby guiding themselves to pose effective questions and question sequences, foster informative feedback processes and enhance the quality of students' learning and performance (Duron et al., 2006).

Additionally, our methodology involved a four-dimensional theoretical scheme that addressed conceptual aspects of learners' understanding from an epistemological standpoint that is primarily normative. Focusing on what students should know if they are to understand biological concepts, this scheme can prove crucial in building MCQ assessment tools because it might help teachers choose MCQ distractors and cluster different MCQs to coherently assess learners' understanding from a knowledge-in-total rather than knowledge-in-pieces perspective.

The fourth (last) dimension, namely, the peculiar ontological, epistemological and methodological assumptions that underlie the conceptual networks to which the taught scientific concepts belong, is crucial to our theoretical scheme. The comparison of these background assumptions with learners' analogous assumptions might shed more light on the notion of misconceptions and how 'misconceptions' should be treated in educational settings.

In recent decades, a shift in thinking about learners' misconceptions has occurred (Maskiewicz & Lineback, 2013). Past misconception research has failed to illuminate the productive role of prior (empirical) knowledge in learning expert concepts or ideas, and by overemphasizing the discontinuity between novice and expert, it has advanced the replacement of the prior concept or idea with the scientific one to the proper instructional strategy. On the other hand, contemporary misconception research has stressed that learners learn by transforming their prior knowledge into more-sophisticated forms and has thus advanced the slow refinement of this knowledge to the proper instructional strategy. However, although contemporary misconception research has been aligned more with constructivist tenets, it encounters problems with showing how preconceptions of learners serve as foundations for acquiring future scientific knowledge. For example, it is questionable whether or how learners refine their naïve ideas towards acquiring the expert ones.

The fourth dimension of our theoretical scheme can provide fruitful answers to these questions because it can offer a deeper understanding of learners' incorrect statements. Transferring the emphasis from information processing to the background assumptions underlying learners' incorrect statements, we suggest that when these latter assumptions appear discrepant with the assumptions composing the epistemological frameworks to which the taught scientific concepts belong, the appropriate instructional strategy for handling misconceptions is replacement. Otherwise, a refinement strategy can suffice. Certainly, this refinement should not disrupt the conceptual borders of the concept-specific epistemological frameworks.

Notes

[1] In propositional logic (i.e., logic in which elementary statements are the basic building blocks; Van der Steen, 1993), modus ponens can be briefly defined as "P implies Q and P is asserted to be true, therefore Q must be true." For example, an argument with the following premises and conclusion is modus ponens:

Premise 1. If Maria is infected H1N1–virus then she will get swine flu. Premise 2. Maria is infected with H1N1–virus. Conclusion. Maria will get swine flu.

Modus ponens is closely related to another valid argument form, modus tollens. Modus tollens can be summarized as "P implies Q and not-Q is asserted to be true, therefore not-P must be true."

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