Health Professions Education

Volume 2 | Issue 1 Article 3

2016-05-04

How Biomedical Misconceptions May Arise and Affect Medical Students' Learning: A Review of Theoretical Perspectives and Empirical Evidence

Elmi Badenhorst
Department of Health Science Education, Faculty of Health Sciences, University of Cape Town, South Africa, elmi.badenhorst@uct.ac.za

Nadia Hartman
Education Development Unit, Faculty of Health Sciences, University of Cape Town, South Africa

Sílvia Mamede
Institute of Medical Education Research Rotterdam, Erasmus MC, and Department of Psychology, Erasmus University Rotterdam, The Netherlands

Recommended Citation

Badenhorst, Elmi; Hartman, Nadia; and Mamede, Sílvia (2016) "How Biomedical Misconceptions May Arise and Affect Medical Students' Learning: A Review of Theoretical Perspectives and Empirical Evidence," *Health Professions Education*: Vol. 2: Iss. 1, Article 3.
DOI: 10.1016/j.hpe.2016.01.005
Available at: https://hpe.researchcommons.org/journal/vol2/iss1/3

Available online at www.sciencedirect.com
ScienceDirect
Health Professions Education 2 (2016) 10–17
www.elsevier.com/locate/hpe

How Biomedical Misconceptions May Arise and Affect Medical Students' Learning: A Review of Theoretical Perspectives and Empirical Evidence

Elmi Badenhorst[a,*], Nadia Hartman[b], Sílvia Mamede[c]

[a]Department of Health Science Education, Faculty of Health Sciences, University of Cape Town, South Africa
[b]Education Development Unit, Faculty of Health Sciences, University of Cape Town, South Africa
[c]Institute of Medical Education Research Rotterdam, Erasmus MC, and Department of Psychology, Erasmus University Rotterdam, The Netherlands

Received 13 January 2016; accepted 17 January 2016
Available online 6 May 2016

Abstract

The debate on whether biomedical knowledge contributes significantly to the clinical reasoning process is on-going. Despite this debate, one cannot underestimate that subjects such as anatomy and physiology play a key role in the understanding of the human body. Misconceptions that exist or arise in biomedical subjects, such as physiology and anatomy, can impact on the learning processes of medical students. The present paper presents an overview of research in the field of biomedical misconceptions and consists of two parts. First, the authors draw on three theoretical frameworks, constructivism, concept formation and element interactivity in complex reasoning, to offer insight as to why misconceptions in biomedical subjects could potentially arise and exist. In the second part, the authors synthesize empirical studies on biomedical misconceptions that draw on similar theoretical frameworks. The limited research available in this field suggests that the three theories discussed in this paper do provide valuable insights into how misconceptions in anatomy and physiology can hamper coherent knowledge construction, and potentially play an obstructive role when students are required to perform complex cognitive tasks such as clinical reasoning.

Keywords: Misconceptions; Medical students; Knowledge construction; Theoretical perspectives

Contents

1. Introduction . . . 11
2. Theoretical frameworks . . . 12
   2.1 Constructivism . . . 12
      2.1.1 Domain generalist theorists . . . 12
      2.1.2 Domain specific theorists – conceptual change . . . 12

*Corresponding author.
E-mail address: elmi.badenhorst@uct.ac.za (E. Badenhorst).
Peer review under responsibility of AMEEMR: the Association for Medical Education in the Eastern Mediterranean Region.

http://dx.doi.org/10.1016/j.hpe.2016.01.005

2.2 Concept formation 13
2.3 Element interactivity 14
3. Studies in the field of biomedical misconceptions 14
4. Conclusion 16
Disclosure 16
Ethical approval 16
Funding 16
Other disclosure 16
Acknowledgements 16
References 16

1. Introduction

In a recent study to explore the nature and frequency of misconceptions in anatomy and physiology under first year medical students at the University of Cape Town, the researchers asked participants to comment on their study methods with regards to the two subjects. This question was included in the study to gain insight into how students interact with new information they encounter. Below are some of the comments made by students.

"I would memorize it. Contrary to popular belief, memorizing a physiological process is much more effective as you are assured that by memorizing the content that you'll use the correct terminology in a test."
"Open the textbook and study it flat out."
"Just read the material over and over again, there is not much understanding to do."
"Make up a song or acronym or whatever, just memorize it."

This paper provides a literature review of theories and synthesizes empirical studies concerning misconceptions in the domain of biomedical subjects. The paper is not exploring study methods of medical students, but the authors took cognizance of the above mentioned remarks to guide us towards a theoretical understanding of why and how biomedical misconceptions potentially arise. In the literature various terms, such as "misconceptions", "naïve beliefs and "alternative conceptions" are used interchangeably to describe the notion of an incorrect understanding of concepts against a certain scientific paradigm.[1,2] For the purpose of this paper a distinction is made between lack of knowledge and misconceptions.[3] Misconceptions are persistent ideas that exist even after instruction.[3] Whilst incomplete knowledge can be addressed by simply adding coherent and scientifically proven knowledge in order to come to grips with new information, misconceptions are robust and resistant to change.[2,4]

Research over the past three decades has shown that students arrive at tertiary institutions with pre-instructional views that are not necessarily supported by current scientific views.[1] One could argue that pre-instructional views that contradict current scientific ideas can easily be eliminated during teaching and learning activities at a tertiary level. However, if these beliefs are firmly held and resistant to change because the framework of these beliefs provided sufficient answers for students to navigate their way successfully through prior cognitive challenges, educators are faced with a challenge. Whether biomedical courses, such as anatomy and physiology, form part of an integrated curriculum, for example drawing on PBL cases, or whether medical curricula offer anatomy and physiology as stand-alone courses during the pre-clinical years, one cannot underestimate that these biomedical subjects are core to a medical student's understanding of the human body. If undergraduate medical students resort to memorizing, and thus not actively seeking understanding when they encounter new information, as was demonstrated in the above mentioned comments, existing misconceptions could continue to inform the learning process or new misconceptions could potentially arise.

The field of research into misconceptions in biology is still emerging as compared to the efforts in the physical sciences. This can be seen from research in conceptual change of science education over the last 20 years as it appears in an analysis of the Students' and Teachers' Conceptions and Science Education (STCSE) data-base, a comprehensive bibliography of papers on studies of conceptions and misconceptions.[5] Analysis of the STCSE database shows that more than four times as many publications are available in the realm of physics and chemistry as in biology.[5] A comprehensive framework making sense of alternative conceptions, and well developed hypotheses about reasons why some biological conceptions are difficult for novices to understand, have yet to be developed.[6] The aim of our paper is therefore to familiarize the reader with research in the field of biomedical misconceptions. The paper consists of two parts. In the first part, we will draw on three theoretical frameworks to offer the reader some insight as to why misconceptions in biomedical subjects could potentially arise and exist. In the second part, we will synthesize empirical studies on biomedical misconceptions among medical students that draw on similar theoretical frameworks.

2. Theoretical frameworks

With regards to the theory part of the paper, we will firstly draw on constructivism (exploring domain general and domain specific theories), then move onto the process of concept formation and finally we will draw on the notion of element interactivity as described in cognitive load theory. These theoretical frameworks arose from a literature review within the much bigger paradigm of learning and are by no means exhaustive in explaining misconceptions. The authors inferred that a coherent understanding of concepts is necessary to construct new knowledge and that the more complex these concepts become, the more difficult it is to make sense of the learning process. The three frameworks presented in this paper where therefore chosen for their relevance to the ways in which a learner interacts with new information, to inform us as to why and how robust misconceptions arise or hamper coherent knowledge construction.

2.1 Constructivism

The first theoretical framework, constructivism, concerns itself mainly with seeing human knowledge as a process where an individual is trying to make sense of his/her environment. This process is a personal cognitive construction by the individual in response to the environment.[7] The learner is therefore not seen as a passive receiver, but actively constructs knowledge in the learning process.[7] Students do not learn from scratch, and they do not learn as a result of knowledge that is simply transferred to them via a certain source.[1] Prior conceptions are key to the process of learning; hence relying on rote learning alone could give rise to misconceptions. As a result of constructing knowledge incoherently, misconceptions may develop, which could hamper further cognitive development. Within this framework of constructivism, we will explore the theories of domain generalist and domain specific theories.

2.1.1 Domain generalist theorists

Domain generalist theorists, such as Ausubel and Piaget, have argued that misconceptions arise during the knowledge construction process, acknowledging the importance of prior knowledge as central to learning.[8] Meaningful learning occurs when new information is incorporated into existing knowledge structures that the learner already has.[9] New information should not simply be “added on” to existing ideas.[10] If the student is not able to fit new information into existing knowledge structures, it becomes compartmentalized, and cannot be used constructively, potentially giving rise to misconceptions. The reason for disparity between new information and existing knowledge structures is often the result of rote learning, which Ausubel defines as “arbitrary, verbatim, non-substantive incorporation of new ideas into cognitive structure”.[8] Similar to Ausubel, Piaget claims that learners use mental patterns to facilitate learning and understanding. These already existing patterns are used to interpret new material.[11] When a learner encounters situations in which his/her existing knowledge patterns cannot explain new information, it results in disequilibrium, where the “mental balance” needs to be restored.[12] The learner will either develop a new pattern of thinking, or modify an old one until equilibration has been reached.[8] Assimilation is therefore the process of doing minor revisions to an existing thinking pattern, while accommodation refers to major restructuring of existing patterns.[11] Misconceptions are therefore often a result of “incorrect” assimilation or accommodation. To put this into perspective, a novice might simply believe that, based on their knowledge of inhalation, exhalation must also be an active process involving muscles because they are not able to understand the interaction between air pressure inside the lungs and atmospheric pressure. Alternatively, in their quest to make sense of the role of “pressure” in breathing out, they might construct a new thinking pattern to explain to themselves that exhalation is a result of the diaphragm “forcing” air out of the lungs. In both cases the learner ends up with a misconception because they cannot construct coherent knowledge, potentially based on their prior knowledge that breathing could be seen as an active process.

2.1.2 Domain specific theorists – conceptual change

Domain specific theorists, on the other hand, argue that misconceptions arise because students are, for whatever reason, not undergoing the necessary process of conceptual change to embrace current scientific knowledge. Conceptual chance is defined as the process of shifting away from naïve beliefs when students are exposed to counter-intuitive concepts.[13] It involves re-organizing existing ideas in order to support current evidence-based knowledge. Although this notion is very similar to the domain generalist view, conceptual change theory is based on Kuhn's notion of a paradigm shift.[14] This notion[14] claims that scientists ascribe to shared beliefs, assumptions, commitments and practices. As new things are discovered, certain concepts can no longer be accommodated to explain anomalies. This process where scientist might need to develop new concepts is called a paradigm shift. Theorists[15] draw on this notion to describe the process when a student has to replace and reorganize central concepts, as previous ideas are no longer adequate to explain certain scientific phenomena. Different to Piaget, this process is not seen as an internal cognitive interaction of the learner trying to find equilibrium based on his/her prior knowledge, but rather the need to re-organize mental structures to accommodate information based on scientific evidence.[16]

Within conceptual change theory, there are many theorists who explain why misconceptions arise within domain specific areas. For a comprehensive overview, the reader is referred to The International Handbook on Conceptual Change.[2] Researchers for example argue that some scientific concepts are difficult to learn because students' current knowledge could be embedded in naïve frameworks that contradict more recent scientifically acceptable frameworks or paradigms.[17–20] These naïve frameworks are continuously re-confirmed by everyday experiences and are difficult to change, as they provide students with a relatively coherent explanation of certain scientific phenomena. Typically students are not aware of these misconceptions in their thinking process, and simply add new knowledge to their current cognitive structures, creating inconsistent thinking. The learning of scientific concepts requires a radical and ontological category shift.[13] The learning difficulties that many students experience when being confronted with scientific material are not necessarily the result of cognitive deficiencies, but often a result of lack of critical thinking, knowledge fragmentation, lack of transfer, poor instruction, and most importantly, having misconceptions that conflict with current scientific research.[17] To change this framework, students experience severe difficulties, as their initial belief provides a "relatively coherent system of explanation"[21] which is based on everyday experience and many years of confirmation. Even though instruction based on counter-intuitive facts will provide students with the "correct" information, it might not necessarily lead to conceptual change, as it does not provide students with all the information they need to revise their current framework. A simplified example of this would be that novices might, even in the face of scientific evidence, hold onto the believe that touching an HIV or TB infected patient is sufficient for becoming infected or that taking excessive amounts of vitamin C and home-made remedies can cure a cold. Educators working with culturally diverse students should also be aware that some students hold onto traditional beliefs that might contradict current scientific evidence.

Students might end up with conflicting ideas between prior and new knowledge because of ontological shifts they have to do in order to categorize concepts.[3] The reason why students find certain biomedical and scientific concepts so hard to learn is because they experience a mismatch between their initial categorization of a concept, and the new learning context. This notion of mismatch is called the Incompatibility Hypothesis.[3] Take for example the concepts of "ions", "electrons" and "molecules". Students might categorize these concepts as "matter" and therefore static in nature, based on representations in textbooks. When confronted with a new learning context, for example to understand movement, current and nerve conduction, student might struggle to "re-classify" these concepts as now not being static, but part of a process. As long as there is incompatibility between prior and new knowledge, the student continuously needs to alternate between two conceptual categories in order to understand them. If new concepts are incompatible with a prior concept, naïve conceptions tend to be robust enough so that it is difficult to overcome it by instruction or confrontation.[18] The same student will display the same misconceptions over time and different contexts. These misconceptions are persistent across different ages and schooling levels and homogenous among different students, so that students display similar misconceptions across historical periods. A typical example of this notion is the misconceptions that many medical students hold with regards to the "double loop system" involving the cardiovascular system. Many students hold on to the misconception that the heart operates in a "single loop", therefore believing that the lungs are autonomous and that blood simply flows from the heart through the body and back. [22]

2.2 Concept formation

The second theoretical framework, linked to the process of negotiating new information, concerns itself with concept formation. In the previous section, we described how misconceptions can arise when constructing new knowledge. In order to construct new knowledge, the learner needs to form an understanding of the various concepts involved. To put this into context, before medical students can understand the cardiovascular system, they need to be familiar with concepts such as arteries, veins and capillaries. In more abstract terms, students need to become familiar with concepts such as mitochondria, ATP, nerve conduction and action potentials to understand muscle movement.

With regards to theories on concept formation one can go back as far as the philosophers Kant, Locke and Mill who argued that a concept is a cognitive unit that has meaning. A concept can therefore be a mental symbol or an abstract idea, defined as a "unit of knowledge". For a comprehensive overview of the process of concept formation, the reader is referred to the work of Medin et al.[23] A more contemporary view[24] to explore the role of threshold concepts, is that concepts are mental representations, understood either as mental images or as word-like symbols in a 'language of thought'. Thought mirrors language, so concepts can be seen as physical entities that relate to and can be understood by symbols or words. On the other hand, abstract concepts can be represented as an act or quality. An abstract concept is therefore not always an image or representation in the mind, but rather an abstraction of the formal concept that derives its ontological status from the action it performs, for example *homeostasis* or *metabolism*. One can therefore argue that if medical students experience problems during the concept formation process (for example, having a simplistic mental representation based on two-dimensional drawings in textbooks, or experiencing difficulties to construct abstract concepts from processes that are not visible to the naked eye, such as *phosphorylation)*, misconceptions could potentially arise. In this regard, language could also play a key role. If the student does not have the necessary scientific and biomedical language to construct the concept, he or she could end up with a misconception.

2.3 Element interactivity

This brings us to the third theoretical perspective on misconceptions in biomedical domains. Many anatomical and physiological structures may appear to be 'simplistic', but in fact, demand a complex range of cognitive actions in the working memory to construct a coherent understanding. In explaining cognitive load theory, complexity is defined as element interactivity.[25] The authors are not drawing on cognitive load theory in detail, but interested readers are directed to research done on the role of this theory in health science education.[25] To explain the role of element interactivity in complexity, an element can be seen as "anything that needs to be understood and learned", and elements that interact heavily with each other, need to be understood *first* before they can be used together in complex tasks.[25] It could explain why students can perform very basic tasks in assessments, such as simply listing three bones or muscles (low level of element interactivity and can be learnt in isolation), but the moment more complex cognitive tasks are required of them, for example to explain a complex physiological process, they seem to struggle. The more elements have to interact with one another to form a coherent understanding of a complex idea, the higher the working memory load becomes.[26] If, for example, students are asked to explain the process of rehydration in the case of severe diarrhea, element interactivity is at play, from the cellular level through to the structure and function of the gastro-intestinal track. The challenge to educators would be to try to identify the level of complexity in order to understand how and why students arrived at a superficial understanding. An important point to remember at this stage is that there is a difference between the way a novice and expert will view an element. One could therefore assume that the expert (lecturer) who possesses all the underlying foundational knowledge to understand the process of rehydration as a single element, might treat it as such in teaching activities, whilst for the novice (student) it might appear to be a simplistic and single element, because the atomic parts, such as cellular structure and osmosis, the role of glucose and salt, which is necessary to understand this concept, is not necessarily interacting with each other for them. The student might then end up with an overtly simplistic understanding of a very complex process, and therefore not be able to develop a coherent understanding when confronted with a scenario of uncertainty, for example, when asked to arrive at a diagnosis and treatment plan involving the gastro-intestinal track.

3. Studies in the field of biomedical misconceptions

The second part of the paper will present examples of empirical studies that have explored how the above-mentioned perspectives show up in practice by investigating medical students' misconceptions. Our intention here is not to present a systematic, comprehensive review of the literature but rather to draw on a few key studies to demonstrate how the theoretical frameworks discussed in the first part of the paper showed up in practice and potentially explain the nature of misconceptions in these subjects. Educational studies in biomedical subjects, such as anatomy and physiology, that have mainly explored teaching and learning challenges not necessarily associated with misconceptions, will therefore be excluded from this discussion.

In one of the earlier studies[26] exploring biomedical misconceptions, researchers drew on constructivism and concept formation to arrive at a conclusion that novices begin their learning with preconceptions that discount a basic understanding of concepts essential for understanding. According to them, misconceptions identified in their study stem from prior learning and interfere with a coherent and integrated understanding of body systems. One such misconception found by the researchers was that heart failure is caused by an oversized heart, which in turn stretches the cardiac muscle fibers. The researchers ascribed this misconception to prior learning and drawings in textbooks that depict a single cardiac muscle fiber. Students became confused as they assumed that it was an intact system, ignoring other properties, such as biochemical and physiological concepts that impact on the system. Although the researchers did not draw on the notion of element interactivity[25] they indicate that a simplistic understanding of complex structures and processes can give rise to misconceptions.

In a study on cognition and expertise, researchers discuss how superior and expert performance in clinical reasoning relates to well-structured and interconnected domain-specific knowledge.[27] They draw on cognitive load theory and conceptual change theory to explain that well-structured domain specific knowledge facilitates expertise in clinical reasoning. In a study done to identify medical students' conceptions of underlying principles in medical physiology, the researchers give an overview of studies conducted to explore misconceptions in physiology.[28] They draw on the work of Patel et al.[29] to explain that a superficial understanding of concepts (concept formation and constructivism) can lead to misconceptions in a novice's understanding of complex physiological processes as this discipline demands a specific conceptual understanding of interrelated systems. In one of the few studies pertaining to the early part of health science students' career, researchers found that first year medical students arrived at university with a substantial range of preconceptions related to the cardio-vascular system, and that only a few of these naïve understandings disappeared after instruction.[30] Furthermore, they found that students with misconceptions performed poorly during clinical reasoning. The researchers drew on conceptual change theory to inform their study and arrived at the conclusion that medical educators should become familiar with domain specific pedagogy to raise awareness of misconceptions in biomedical subjects, specifically for the impact it has on clinical reasoning. Researchers[31] also draw on conceptual change theory in a study to explore first-year medical students' resistance to conceptual change concerning the central cardiovascular system. In their study they give an overview of studies done with regards to misconceptions concerning the cardio-vascular system. The researchers conclude their study with the suggestion that a small percentage of students need help with the integration of anatomical and physiological knowledge as they are unable to construct a coherent understanding of the cardiovascular system. They caution educators that students who stay at a level of rote learning in biomedical subjects may never reach a level of meaningful learning and that misconceptions in this regard could potentially impact negatively on the clinical reasoning process.

While reporting on a study on misconceptions in respiratory physiology, Cliff[32] reviews similar studies in the field and draws on conceptual change[15,33] to explain that misconceptions can be surprisingly resistant when educators use more conventional teaching approaches. This study explored four misconceptions concerning the respiratory system and showed how a case study was used to remedy students' naïve understanding of oxygen transport in the blood. The researcher cautions educators however that some misconceptions are robust, and furthermore, alludes to the fact that misconceptions can arise during teaching activities when students construct an understanding of the respiratory system. Cliff[32] suggests that a variety of assessment tools, concept mapping and clinical interviews can assist educators to gain insight into students' thinking processes and to explore whether conceptual change occurred in specific domains.

A recent study[34] draws on constructivism, concept formation and element interactivity to explore lecturers' perceptions of first year medical students' misconceptions in anatomy and physiology. In this study nine potential sources of misconceptions were identified and linked to the above mentioned theoretical frameworks. The researchers found that misconceptions could arise as a result of mental operations during the concept formation process when students have to move between micro- and macro-levels, apply three-dimensional thinking, and form a visio-spatial understanding of positioning and size of anatomical structures. Language barriers were also identified as a potential source of misconceptions during the concept formation process. Misconceptions that arise when having to apply causal reasoning and integration of knowledge can be linked to a resistance in students' cognitive operations to undergo conceptual change. Their study found that considerable misconceptions arise when students get confused between matter and process.[22] Teaching and learning styles can also give rise to misconceptions, as students are not necessarily constructing coherent knowledge. In this regard, their finding corroborated Ausubel's theory[9] of compartmentalized knowledge construction to indicate that rote learning and ineffective instruction can prevent meaningful learning. From their results, it appears that students end up with misconceptions, because they study anatomy and physiology in isolation, and do not necessarily transfer knowledge from structures to process/functions. This poses a challenge to educators to select pedagogic strategies to avoid learning in silos. In this study[34] the three theoretical frameworks presented in this paper, are synthesized, so educators get a nuanced understanding of how biomedical misconceptions can arise during knowledge construction. This study further points to potential pedagogical interventions that will assist educators to recognize and address these misconceptions.

This part of the paper aimed to illustrate existing research in the field of biomedical misconceptions by discussing key studies that draw on the theoretical framework that was reviewed in the first part of the paper. As research in this particular area is limited, future studies are recommended to explore whether misconceptions held by medical students can be further explained by drawing on theories pertaining to constructivism, concept formation and element interactivity in the understanding of complex constructs.

4. Conclusion

In conclusion, the debate on whether biomedical knowledge does indeed contribute significantly to the clinical reasoning process is on-going. Despite this debate, one cannot underestimate that subjects such as anatomy and physiology play a key role in the understanding of the human body. The limited research available suggests that the three theories discussed in this paper do provide valuable insights into how misconceptions in anatomy and physiology can hamper coherent knowledge construction, and potentially play an obstructive role when students are required to perform complex cognitive tasks such as clinical reasoning. Similar follow-up studies are required to test the explanatory power of synthesizing the three theories, particularly in relation to senior students. Future studies should also explore how pedagogical strategies can draw on the theoretical framework we have put forward, to address misconceptions and allow for coherent knowledge construction.

Disclosure

Ethical approval

Ethical approval has been Granted from the University of Cape Town Human Ethics Research Committee (18 December 2012, *HREC Ref:* 563/2012).

Funding

None.

Other disclosure

None.

Acknowledgements

This project was made possible by the URC Short Research Visit grant, as well as the Researcher Development Grant. Both grants were allocated to the first author by the University of Cape Town, South Africa in 2012.

References

1. Treagust D, Duit R. Conceptual change: a discussion of theoretical, methodological and practical challenges for science education. *Cult Stud Sci Educ*. 2008;29(2):297–328.
2. Vosniadou S. *International Handbook Of Research On Conceptual Change*. Washington, D.C.: Routledge; 2008.
3. Chi MTH. Why some misconceptions are robust. Commonsense conceptions of emergent processes. *J Learn Sci*. 2005;14(2): 161–199.
4. Carey S, Spelke E. Domain-specific knowledge and conceptual change. In: Hirschfeld LA, Gelman SA, editors. *Mapping the Mind: Domain Specificity in Cognition and Culture*. New York: Cambridge University Press; 1994.
5. Duit R. *Bibliography STCSE: Students' and Teachers' Conceptions and Science Education*. Germany: Leibniz Institute for Science Education Kiel, IPN; 2004. stcse/stcse.html.
6. Duit R, Treagust DF. Conceptual change – a powerful framework for improving science teaching and learning. *Int J Sci Educ*. 2003;25(6):671–688.
7. Duit R. The constructivist view in science education. What it has to offer and what should not be expected from it. *Investig Ensino Ciênc*. 1996;1(1):40–75.
8. Cakir M. Constructivist approaches to learning in science and their implications for science pedagogy: a literature review. *Int J Environ Sci Educ*. 2008;3(4):193–206.
9. Ausubel DP, Novak JD, Hanesian H. *Educational Psychology: a Cognitive View*. New York: Holt, Rinehart and Winston; 1968.

10. Novak JD. *Learning, Creating, and Using Knowledge. Concept Maps as Facilitative Tools in Schools and Corporations*. Mahwaw: Lawrence Erlbaum; 1998.
11. Piaget J. *Success and Understanding*. Harvard: Harvard University Press; 1978.
12. Piaget J. *Adaptation and Intelligence: Organic Selection and Phenocopy*. Chicago: University of Chicago Press; 1980.
13. Vosniadou S, Verschaffel L. The conceptual change approach to mathematics learning and teaching. *Learn Instr.* 2004;14(5): 445–548.
14. Kuhn T. *The Structure of Scientific Revolutions*, Anniversary ed., Chicago: University of Chigago Press; 2012.
15. Posner GJ, Strike KA, Hewson PW, Gertzog WA. Accommodation of a scientific conception: toward a theory of conceptual change. *Sci Educ.* 1982;66(2):211–227.
16. Larsson Å, Halldén O. A structural view on the emergence of a conception: conceptual change as radical reconstruction of contexts. *Sci Educ.* 2010;94(4):640–664.
17. Vosniadou S. The cognitive–situative divide and the problem of conceptual change. *Educ Psychol.* 2007;42(1): 55–66http://dx.doi.org/10.1080/00461520709336918.
18. Chi MTH, De Leeuw N, Chiu MH, Lavancher C. Eliciting self-explanations improves understanding. *Cogn Sci.* 1994;18(3): 439–477.
19. Carey S. Knowledge acquitition-enrichment or conceptual change?. In: Carey S, Gelman, editors. *The Epigenesis of Mind: Essays on Biology and Cognition*. Hillsdale NJ: L. Erlbaum Associates; 1991.
20. Hatano G, Inagaki K. Qualitative changes in intuitive biology. *Eur J Psychol Educ.* 1997;12(2):111–130.
21. Vosniadou S. Capturing and modeling the process of conceptual change. *Learn Instr.* 1994;4(1):45–69.
22. Chi MTH. Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In: Vosniadou S, editor. *International Handbook of Research on Conceptual Change*. New York: Routledge; 2008.
23. Medin DL, Smith EE. Concepts and concept formation. *Annu Rev Psychol.* 1984;35(1):113–138.
24. Rowbottom DP. Demystifying threshold concepts. *J Philos Educ.* 2007;41(2):263–270.
25. Sweller, J. How the human cognitive system deals with complexity. *Handling Complexity in Learning Environments: Theory and Research*; 2006:13–25.
26. Feltovich PJ, Spiro RJ, Coulson RL. The nature of conceptual understanding in biomedicine: the deep structure of complex ideas and the development of misconceptions. In: Evans D, Patel V, editors. *Cognitive Science in Medicine: Biomedical Modeling*. Cambridge, MA: MIT Press; 1989.
27. Patel VL, Glaser R, Arocha JF. Cognition and expertise: acquisition of medical competence. *Clin Investig Med.* 2000;23 (4):256–260.
28. Fyrenius A, Silén C, Wirell S. Students' conceptions of underlying principles in medical physiology: an interview study of medical students' understanding in a PBL curriculum. *Adv Physiol Educ.* 2007;31(4):364–369.
29. Patel VL, Kaufman DR, Magder S. Causal explanation of complex physiological concepts by medical students. *Int J Sci Educ.* 1991;13:171–185http://dx.doi.org/10.1080/0950069910130204.
30. Ahopelto I, Mikkilä-Erdmann M, Olkinuora E, Kääpä P. A follow-up study of medical students' biomedical understanding and clinical reasoning concerning the cardiovascular system. *Adv Physiol Educ.* 2011;16(5):655–668.
31. Mikkilä-Erdmann M, Södervik I, Vilppu H, Kääpä P, Olkinuora E. First-year medical students' conceptual understanding of and resistance to conceptual change concerning the central cardiovascular system. *Instr Sci.* 2012;40(5):745–754.
32. Cliff WH. Case study analysis and the remediation of misconceptions about respiratory physiology. *Adv Physiol Educ.* 2006;30(4):215–223.
33. Strike KA, Posner GJ. Conceptual change and science teaching. *Int J Sci Educ.* 1982;4(3):231–240.
34. Badenhorst E, Mamede S, Hartman N, Schmidt HG. Exploring lecturers' views of first-year health science students' misconceptions in biomedical domains. *Adv Health Sci Educ.* 2014;20(2): 403–420.

Elmi Badenhorst is senior lecturer at the Department of Health Science Education, University of Cape Town, South Africa.

Nadia Hartman is senior lecturer at the Department of Health Science Education, University of Cape Town, South Africa.

Silvia Mamede is associate professor at the Department of Psychology, Erasmus University and Institute of Medical Education Research, Rotterdam.