At the heart of learning: navigating towards educational neuroscience in health professions education

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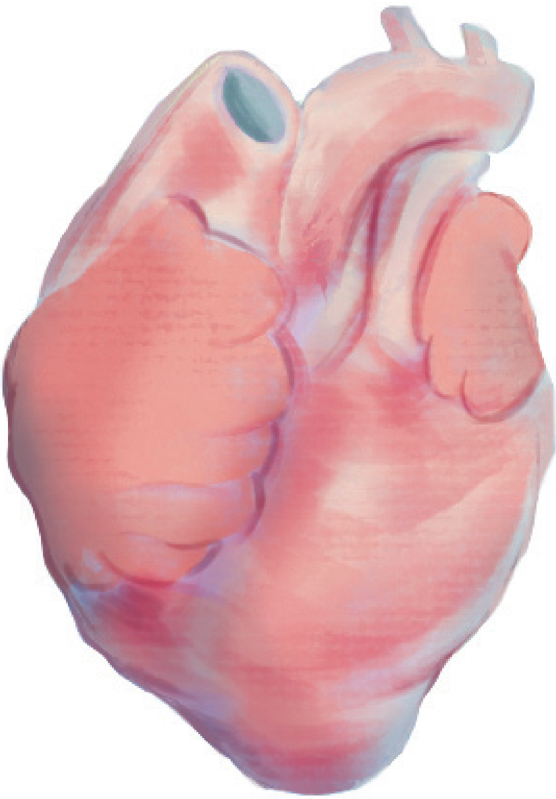

The origins of medical students' misconceptions and misunderstandings in cardiovascular physiology

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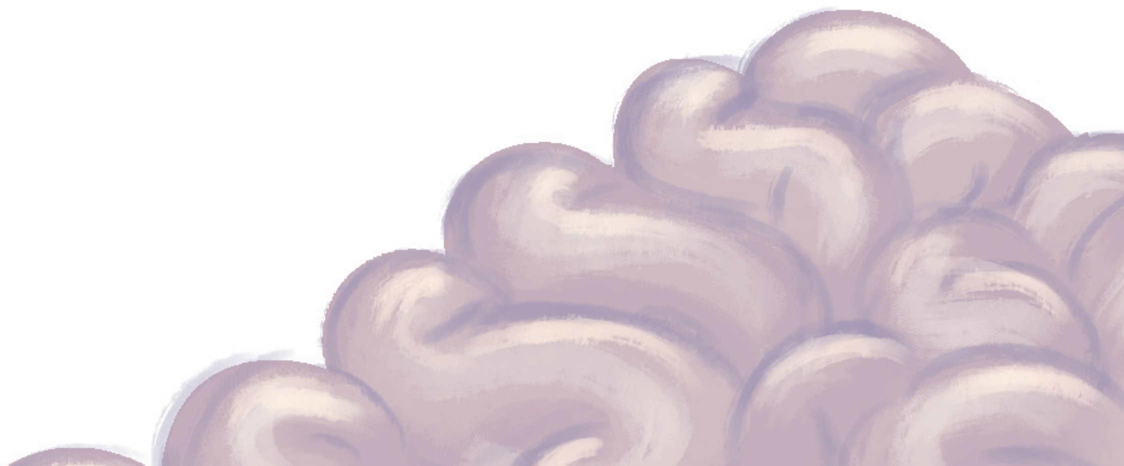

Abstract

Physiology is acknowledged as a challenging subject for medical students. Many students seem to have a poor understanding of concepts underlying physiological processes. However, the specific origins of inaccurate conceptual understanding remain underinvestigated in medical education. This study explores students' fallacies in conceptual understanding regarding the interrelated concepts of pressure, flow and resistance. Qualitative conventional content analysis was carried out on medical students' ($N = 156$) written responses to a formative test. In total, seven categories emerged to describe students' fallacies; characteristics of substances, characteristics of structures, characteristics of quantities, cause-effect relationships, assumptions, systems thinking, and mathematical reasoning. This categorical distinction revealed various origins of poor conceptual understanding. These origins were linked to different educational theories on concept learning, including ontological miscategorisation and complexity-reduction. Besides these theoretical implications, our outcomes practically inform educators on potential fallacies in students' conceptual understanding that may need to be addressed. We suggest that educators may be helped by distinguishing between misconceptions and misunderstandings in their teaching. Misconceptions are robust incorrect scientific beliefs that are difficult to alleviate because the learner should undergo conceptual change, whereas misunderstandings are flaws in one's thinking that may be quickly resolved by making the learner aware of these flaws through direct instruction. Accordingly, developing conceptual change instructions and creating awareness by explicitly addressing misconceptions and misunderstandings is an important step towards developing effective instructional designs that may advance physiology education.

Introduction

Medical education should expand students' comprehension of human body functions. This is challenging as students find it difficult to grasp an accurate understanding of the underlying physiological concepts (Michael et al., 2002; Modell, 2007). Students' conceptual understanding of medical physiology has shown to be rather limited and difficult to enhance through traditional teaching methods (Palizvan et al., 2013; Ahopelto et al., 2011). The cause may lie in the so called misconception phenomenon that refers to a learner's incorrect mental model which is incongruent with the accepted scientific model (Posner & Strike, 1982; Chi et al., 1994a).

Misconceptions in medical physiology have been demonstrated repeatedly (Michael et al., 2002; Palizvan et al., 2013; Versteeg et al., 2019). Educational theorists working on concept formation and conceptual change have provided various explanations for the existence of misconceptions and the difficulty in debunking them. For instance, students may enter their medical education with naive beliefs about concepts, based on everyday life experiences or incorrect inferences from previous education (Posner & Strike, 1982; Chi et al., 1994a; Feltovich et al., 1988). These naive beliefs appear highly resistant to change, since they may provide a system of explanation which seems relatively internally coherent (Vosniadou, 1994).

Although there is ample research on students' level of conceptual understanding in medical physiology education, the specific origins of inaccurate conceptual understanding remain underinvestigated (Fyrenius et al., 2007). In this study, our primary aim was to qualitatively explore the spectrum of students' inaccurate understanding regarding the interrelated concepts of pressure, flow and resistance. These concepts are of particular interest, since previous studies showed that medical students' ability to correctly understand these concepts and the relationships between them appeared very limited (Versteeg et al., 2019; Versteeg et al., 2019). Findings may have implications for teaching and learning of these concepts specifically. Moreover, we expect our results to enrich theoretical frameworks on concept learning in general so they may also be transferred to other contexts.

Methods

Context of the study

The study was carried out in the medical school at Leiden University Medical Center. One-hundred fifty-six first-year medical students (N = 156) participated in this study, which was performed during a small group teaching seminar on cardiovascular physiology. This seminar was part of a compulsory, 8-weeks course on integrative cardiovascular, respiratory and kidney physiology at the beginning of the second semester. In the first semester, students had completed courses on cellular and molecular human biology. During the physiology course, students met in seminar groups (12-17 students per group) once a week for 2-4 hours. The total amount of scheduled time for the course is, on average, 20 hours/week. Besides the seminars, scheduled educational activities are lectures, practical sessions, computer sessions, and interactive sessions with experts. Summative assessments are performed half-way and at the end of the course by exams with multiple choice questions. Additionally, students earn credits by writing an essay. The seminars focus on solving clinically-based scenarios in small-group sessions led by an expert. This study was performed during the first seminar of the course. As preparation for the seminar the students were instructed to study a textbook section (Boron & Boulpaep, Medical Physiology, 3rd ed, p.412-420) on the basics of hemodynamics. Briefly, this sections handles the definitions of flow, (driving) pressure and resistance, and how these are related via Ohm's law of hydrodynamics. It explains how vascular resistance is related to the length and diameter of a vessel and the viscosity of the fluid via the Poiseuille equation, and under which conditions this equation is valid (or at least a good approximation). Furthermore, it is explained how overall resistance can be calculated in case of multiple resistances arranged in series and/or in parallel. These topics were also introduced and explained in a prior plenary lecture.

Study design

During the seminar, students were given a formative test consisting of eight open-ended questions. These were two-tier questions; the first tier was a multiple choice question, e.g. Q: "what happens to the bloodflow?" A: "Increases/decreases/stays the same", and the second tier was an open-ended question asking to explain one's answer to the first tier. The eight questions were divided in two sets of four, for which students received the correct explanations of the first set before answering the second set. All questions were related to the concepts of flow, pressure and resistance of blood in the cardiovascular system. Students had four minutes per question to provide an answer to the multiple choice question plus a written explanation All questions and correct explanations were designed by a physiology teacher (PS) with longstanding experience in cardiovascular research and teaching, and designing and reviewing exam questions.

Data analysis

Using a qualitative approach, the written explanations were first independently coded by two researchers (MV and PS). A conventional content analysis was performed, which means that the codes were derived directly from the text data (Hsieh & Shannon (2005). The team members read the answers and performed open coding in isolation. The team met on a regular basis after coding each question to review the code structure and to resolve any discrepancies between codes. The coding process was iterative as codes were adjusted until full agreement was reached. For each of the four initial questions, a separate codebook was established. Subsequently, these codebooks were applied to the second set of questions and adjusted when needed. In the final stage, all codebooks were merged to identify overarching themes in the data. Educational theories on concept learning were informative during this final stage and helped to put these overarching themes into broader perspective (Chi et al., 1994a; Feltovich et al., 1988).

Ethical considerations

Students participated in this study on a voluntary basis and they could withdraw their consent at any time. Students received no additional credit for participating in the research. They were informed that all data would be anonymised and test performance had no effect on their course grade. The study protocol was approved by the LUMC Educational Research Review Board (ERRB).

Results

From the analysis seven categories emerged, labeled as: characteristics of substances, characteristics of structures, characteristics of quantities, cause-effect relationships, assumptions, systems thinking, and mathematical reasoning. The labeled categories are summarised in Table 1 with a description and clarified by examples. In the text, quotes from students' (S1-S156) answers to the various questions (Q1-Q8) can be found.

Characteristics of substances

Students described a substance using characteristics that physically do not belong to that specific substance. For instance, students stated that blood, i.e. a substance: liquid, is compressed when a vessel narrows. However, in fact, liquids are incompressible unlike gases. Some argued that the blood is compressed either within or before the narrowed section, resulting in locally increased blood pressure. This fallacy was often found when the question involved vasoconstriction.

> "Blood is compressed due to the vessel narrowing, resulting in increased pressure." (S1, Q4)

Characteristics of structures

Students incorrectly related specific characteristics to physical structures, e.g. series and parallel vascular networks, leading to incorrect implications or effects. For instance, students stated that in case of a parallel vessel network, i.e. a structure, blood will always be equally distributed between the vessels, implying that this distribution of flow occurs independent of the vessel's characteristics. Also, some students wrote down that in a parallel vascular system, all blood will flow to the one vessel with the lowest resistance. However, in fact, blood is distributed according to the characteristics of all vessels in the system. This fallacy was often found in questions involving a parallel system of either two or three vessels of which one was partially or fully restricted.

> "By restricting one of three parallel vessels, more blood has to pass the two remaining vessels. One of the remaining vessels has a higher resistance due to its smaller diameter. Blood will choose the easy way and will flow through the other vessel…" (S56, Q2)

Characteristics of quantities

Students used an incorrect definition of a quantity or attributed the wrong characteristics to a quantity. They often seemed to either interchange or equate quantities that are fundamentally different and thereby assign the wrong characteristics to a specific quantity. For instance, students stated that a blood vessel has a maximum capacity [a characteristic] beyond which flow [a quantity] cannot increase because it does not "fit". These students appear to have interchanged or equated the quantities flow and volume. In fact, even in a completely stiff tube, in which a volume change would be impossible, flow will always increase when perfusion pressure increases (although the rate of increase declines when flow becomes turbulent).

> "Flow increases, but the capacity of the blood vessel is not enough to double the flow." (S68, Q3)

Cause-effect relationships

Students made incorrect or unjustified inferences. For incorrect inferences, cause and effect were sometimes inversed, e.g. a change in flow causes a change in resistance, instead of the other way around. For unjustified inferences, students tended to describe cause-effect relationships between two quantities, e.g. resistance and flow, while ignoring the effect of a third quantity, e.g. pressure.

> "Flow in vessel #1 has halved, causing the resistance to double." (S102, Q7)

Assumptions

Students made incorrect or unfounded assumptions that led to an incorrect conclusion. This usually entailed the incorrect assumption that either the flow, the pressure or the resistance remained constant and thereby ignoring the effect of its actual change, leading to an incorrect conclusion, e.g. many students stated that when one of the vessels in a parallel structure is blocked all flow previously flowing through that vessel is now rerouted through the other parallel vessels. This indicates that the students assumed that the total flow remained constant. This is generally not correct because the vessel blockage implies that total resistance increased and thus, unless perfusion pressure increased, total flow actually decreased.

> "The ΔP stays the same and the R stays the same too, so the flow does not change." (S57, Q2)

Systems thinking

Students mentioned that local changes only have local effects. They did not consider or recognise the context of the system and only reasoned by considering an isolated part of the system. For instance, some students thought that local alterations in the system, such as a vessel narrowing, would only have an effect on local flow or local pressure and many students argued that upstream pressures are not affected by more down-stream alterations in vessel diameter.

> "The vasoconstriction happens after the place were pressure is measured. So, at the place of the pressure sensor the resistance and flow remain unchanged, so ΔP should not have changed either." (S23, Q4)

Mathematical reasoning

Students showed difficulty in interpreting and applying mathematical formulas or mathematical rules. For instance, some students incorrectly interchanged

Table 1 | Categories of students' fallacies in conceptual understanding.

Category	Description	Example
Characteristics of substances	Incorrect assignment of a certain characteristic to a substance.	Blood can be compressed to a smaller volume.
Characteristics of structures	Incorrect implications or effects of a specific physical structure.	Blood will always be equally distributed between parallel vessels An additional resistance always causes increased total resistance.
Characteristics of quantities	Incorrect interpretation or definition of a quantity, or interchanging of quantities.	A vessel has a maximum capacity beyond which flow cannot increase. If there is still space for more flow, pressure will not increase. If a vessel is blocked its resistance disappears.
Cause-effect relationships	Incorrect or incomplete inferences.	Increased flow causes reduced resistance. If resistance doubles, then pressure drop across the resistance also doubles.
Assumptions	Incorrect or unfounded assumptions.	Flow always remains unchanged, e.g. when a vessel narrowing occurs.
Systems thinking	Incorrect notion that local changes only have local effects and are independent of the system as a whole.	Pressure changes only in the area of a vessel narrowing
Mathematical reasoning	Incorrect application or interpretation of formulas or mathematical rules.	If resistance decreases and pressure increases then flow remains constant, i.e. the net effect is zero.

percentages, fractions, differences and ratios. Furthermore, some students reasoned that if two variables in an equation change in the opposite direction, these effects will cancel each other out resulting in a net effect of zero.

> "R = (P decreases) / (F increases). If the denominator increases and the numerator decreases, they will cancel each other out." (S155, Q1).

Discussion

Many medical students seem to have a poor understanding of the concepts underlying physiological processes (Michael et al., 2002; Modell, 2007; Versteeg et al., 2019). However, the origins of inadequate conceptual understanding have received limited attention. This study qualitatively explored students' fallacies in conceptual understanding. The content was focused on the interrelated concepts of pressure, flow and vascular resistance in the cardiovascular system. A qualitative analysis of students' answers to open-ended questions on these topics revealed various inconsistencies in conceptual understanding, which were sorted in seven emerging categories. Here, we discuss our findings in the light of existing educational theories on concept learning. Moreover, we elaborate on the relevance of our qualitative approach for developing effective instructional designs in order to advance physiology education.

Educational theories on concept learning

The fallacies in students' descriptions of characteristics of substances, structures, and quantities align with existing educational theories on concept learning namely, ontological miscategorisation, static bias, and complexity-reduction.

Ontological miscategorisation

The fallacies on the characteristics of substances and structures fit the idea of Chi and colleagues that concepts can be "ontologically" miscategorised and that the misconception can be alleviated by reassigning the concept to its right category (Chi & Roscoe, 2002). For instance, the fallacy that blood can be compressed was often used as an incorrect justification for changes in blood pressure and flow. In this case, describing blood as something that can be compressed may imply that students conceive of blood as a gas which is different from the tangible category of liquids (Vosniadou, 1994). Similar ontological miscategorisations could be identified in the fallacies that flow will only influence pressure if there is not enough space in the circulatory system, or that blood does not fit, or that resistance can disappear.

Static bias

Furthermore, our findings related to the fallacies on the characteristics of quantities indicated that students have difficulty to distinguish between physical quantities. This aligns with Feltovich and colleagues' idea, named the static bias (Feltovich et al., 1988). In static biases, a dynamic concept such as flow is treated as a static concept such as volume leading to incorrect inferences. Equating blood flow with blood volume was done frequently by students in our study, and is a form of inconsistent thinking that has already been described in previous literature (Feltovich et al., 1993). Feltovich and colleagues (2012) have noted similar examples related to cardiac output, in which the rate of blood flow is often treated by students as changes in blood volume. Following this line of reasoning, cardiac output would increase blood volume, and blood pressure in the veins accordingly.

Complexity-reduction

Our findings indicate that various categories, i.e. cause-effect relationships, assumptions, and systems thinking, comprise maladaptive ways of thinking that relate to the complexity-reduction idea of Feltovich et al. (1998). According to this idea students attempt to underdimensionalise concepts, breaking them down in separate operative variables instead of dealing with the complexity of interactions. For example, the oversimplification of cause-effect relationships was clearly evident as students tended to write about one cause leading to one effect. Also, some students described multiple one to one cause-effect relationships, but did not consider the conceptual integration of the relationships. Another example refers to the unfounded assumptions students made, which generally entailed that one of the variables did not alter. This allows one to reason with only two remaining variables, thereby reducing complexity. Complexity-reduction can also be found in systems thinking, where students would often apply a local characteristic to the complete system or structure or vice versa, e.g. the total pressure drop (ΔP) remains unchanged, therefore, the ΔP of a specific part of the system also remains unchanged. According to Feltovich et al. (1988), these reductive tendencies are readily adopted not only due to cognitive ease, but also through reinforcement of the educational system. Spiro referred to this phenomenon as an unintended conspiracy of convenience in which simplification of the material in textbooks, lecture slides, assignments, etcetera, makes teaching and learning easier for both educators and students (Spiro et al., 1987). As stated by Feltovich and Spiro, complexity-reduction can form a source of misconceptions.

Multiplicative and proportional reasoning

Regarding mathematical concepts, our findings showed that students have difficulty understanding the differences between fractions (or ratios) and percentages. These concepts belong to the multiplicative conceptual field (Vergnaud, 1983). There is a long history of research illustrating that learners find it hard to understand such multiplicative concepts (Behr et al., 1992). It appears difficult to get a good grasp of these concepts partially because they require reconceptualization of the notion of unit and because they call for operating with composite units instead of singleton units (Sowder et al., 1988). Misconceptions may arise when the distinction between fractions and proportional reasoning is not made explicit or when these concepts are not taught in an integrated way.

In summary, our emerged categories align with various existing theoretical frameworks on concept learning. We believe they can be transferred to other physiological contexts to inform educators and researchers about the origins of poor conceptual understanding in medical physiology education.

Practical implications

Exploring students' conceptual understanding has yielded outcomes that may have important practical implications for teaching medical physiology. For instance, our findings illustrate the conceptual areas that are most likely difficult to understand for students and which educators may focus on during their teaching.

Furthermore, our findings indicated that students have difficulty understanding and applying various mathematical concepts such as fractions and ratios in the medical physiology context. This implies that medical education would benefit from additional reinforcement of mathematical skills. There are only few studies addressing mathematical thinking in medical school, so further research is needed to indicate students' needs (de Leon, 2018).

Finally, we would like to suggest that educational practice could benefit from a distinction between misconceptions and misunderstandings (Trotskovsky et al., 2013). Misconceptions are very robust ideas that are incongruent with current scientific views (Posner & Strike, 1982; Chi et al., 1994a). In such cases, correction requires a fundamental conceptual change and associated conceptual change instructions (Ahopelto et al., 2011; Alparslan et al., 2003). On the other hand, a misunderstanding is considered an incorrect interpretation or understanding of something that can often be corrected readily by direct instruction. In our findings, we identified categories that may fit the group of misconceptions, namely; characteristics of substances, structures and quantities, which frequently require ontological shifts. The categories that may be considered forms of misunderstandings are cause-effect relationships, assumptions, and systems thinking. To our knowledge, such a distinction between misunderstandings and misconceptions has not been described before in physiology and may form a relevant contribution to views on concept learning in physiology education.

In general, educators should create awareness among students about these common misconceptions and misunderstandings during their teaching, thereby facilitating concept learning. We believe that these outcomes do not only have direct consequences for the specific concepts that were examined in this study, but can also be transferred to other contexts in medical physiology education. Namely, having accurate mathematical knowledge or being able to distinguish between static and dynamic concepts are general skills that will also benefit scientific reasoning in, e.g., renal and lung physiology. Future studies could further investigate how these findings can be used to optimise instructional designs in the medical curriculum.

Methodological considerations

The task was a written assignment and for practical reasons a time limit was set to answer each question. Both factors may have influenced to the completeness of responses. We cannot rule out the possibility that responses would have been more extensive and detailed if the task had been performed verbally or without time constraints. However, the written approach allowed us to perform the study with a relatively large cohort in a classroom setting that was part of the standard curriculum. We aimed for such a natural learning environment to obtain authentic responses from students that were actually enrolled in the physiology course. Furthermore, the study design included two sets of four questions each and the students were allowed to review the answers to the first set of questions before starting with the second set. This may have enhanced students' prior knowledge for this second set which may have increased the variety of responses, thereby aiding us in gaining a broader spectrum of students' understanding in this qualitative study. Lastly, a conventional content analysis, rather than a summative or directed content analysis, was chosen to gain qualitative information from student responses without imposing preconceived theoretical frameworks or categories (Hsieh & Shannon, 2005).

Conclusion

This study reveals new insights into the understanding of physiology concepts or lack thereof by first-year medical students using a qualitative approach. A conventional content analysis on students' written responses yielded various categories that entail different origins of thinking fallacies. These categories are: characteristics of substances, characteristics of structures, characteristics of quantities, cause-effect relationships, assumptions, systems thinking, and mathematical reasoning. Acknowledgement of these different types of inadequate conceptual understanding may help educators and researchers to develop more effective instructional designs in order to advance medical physiology education.