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Debunking key and lock biology: Exploring the prevalence and persistence of students' misconceptions on the nature and flexibility of molecular interactions

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Abstract

Unless directly addressed, misconceptions can persist even in particularly capable students attending elite programs. To explore the presumptions that undergraduates of two distinguished Swiss universities have common biological misconceptions, we have used the Biological Concepts Instrument (BCI) in a pre-post-test approach [1]. We find that, after 1.5 years of studying biology, students' performance on many BCI questions is still weak, particularly on concepts related to molecular interactions including diffusion or energetic properties of molecules. Additionally, students' responses are persistently influenced by misleading analogies such as the key and lock mechanism of molecular interactions. Our investigation demonstrates that the limitations of analogies, when used to explain biological processes, need to be explicitly articulated to students in an interdisciplinary perspective.

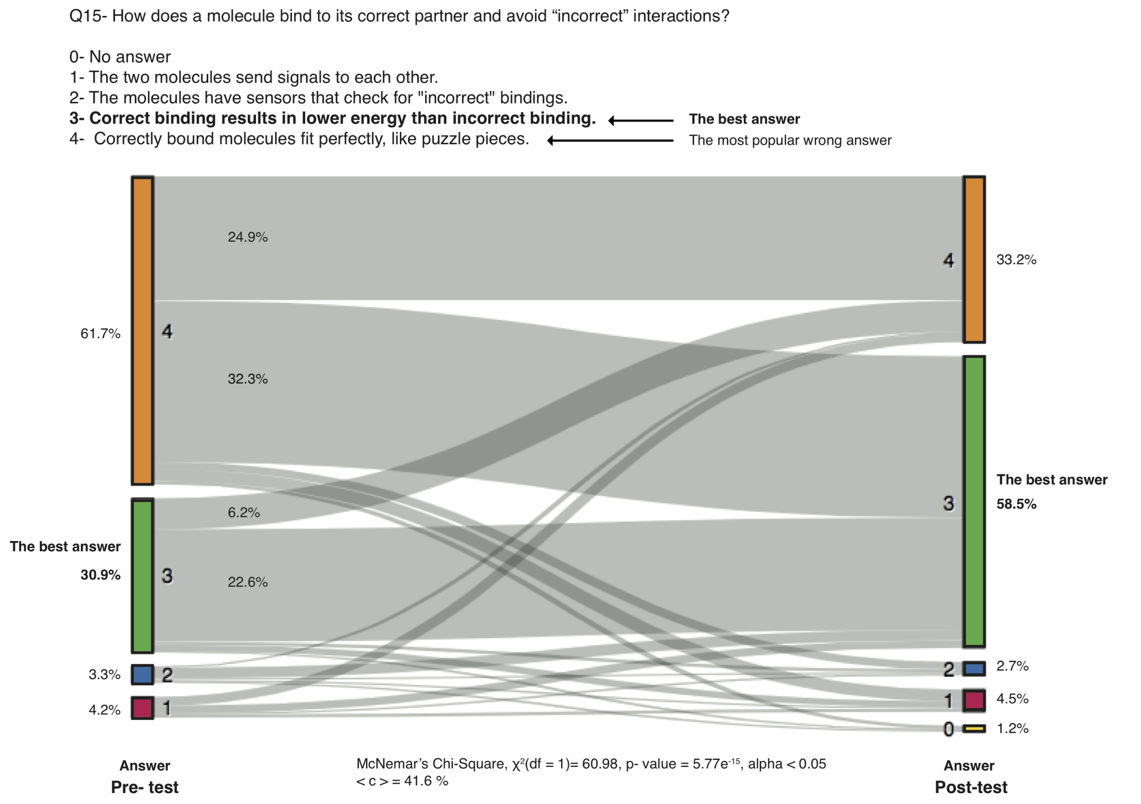
Introduction

Many students demonstrate a naive understanding or unrecognized misconceptions concerning molecular interactions [2] [3] [4] [5]. Misconceptions often go unnoticed and persist during the course of instruction if not addressed [6]. The lock and key or the ball (atoms) and stick (bonds) model often used to visualize molecular structures can lead students to conclude that molecules are rigid rather than flexible conformational structures that either fit together perfectly or do not fit at all (a dichotomous interaction) [7]. Such analogical models can distort the physicochemical concepts involved, such as the rotation of parts of molecules around single bonds, as well as bond stretching and bending, driven by thermal motions [8]. A related issue involves an understanding of how molecules "find" each other, interact with one another, and come apart again. Diffusion-based (molecular collision-driven) stochastic movements are often misunderstood [9] [10] [11]. The Biological Concepts Instrument (BCI) used in the current project can reveal the presence and persistence of misconceptions related to fundamental concepts in biology [1]. This questionnaire consists of multiple choice questions developed through extensive researches on student interviews or student responses to open-ended questions [11].

Objective

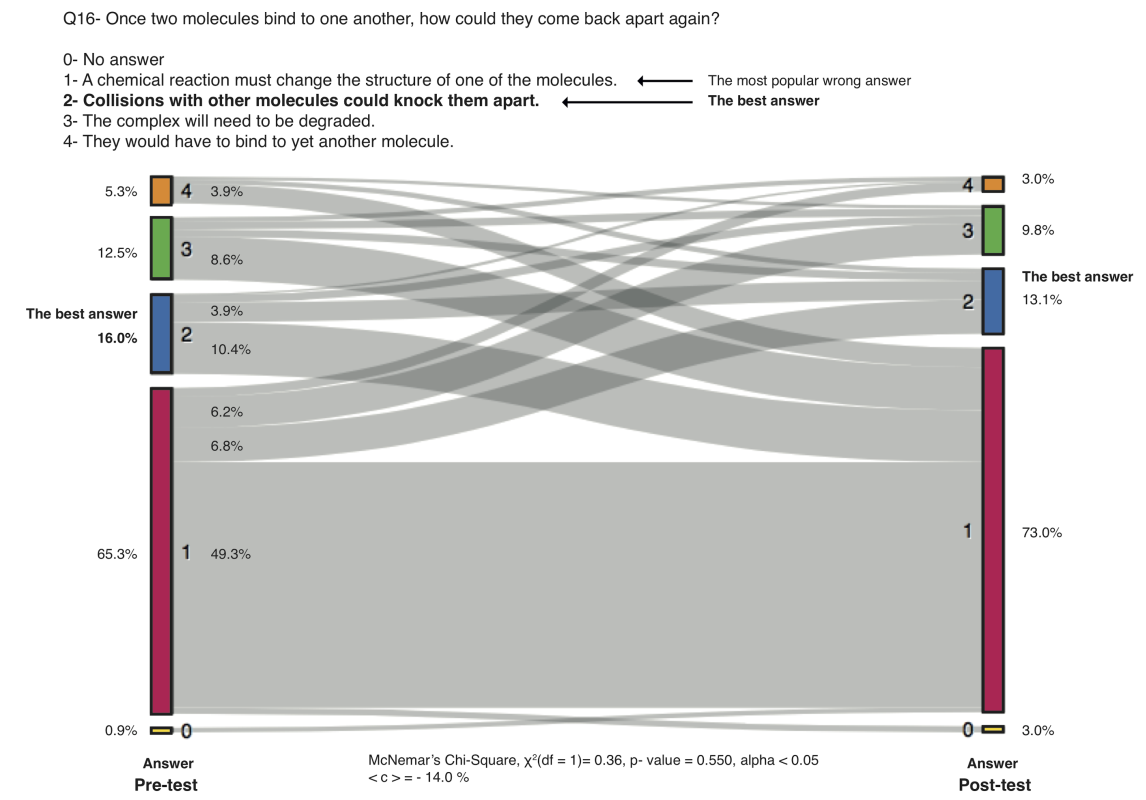
This study explores the presence and persistence of misconceptions in students' understanding using the BCI [1] through a pre- and post-test approach (separated by 1.5 years) to provide a measure of conceptual change over time. The participants were two cohorts of undergraduates enrolled in biology introductory courses in two distinguished Swiss universities.

Figure 1



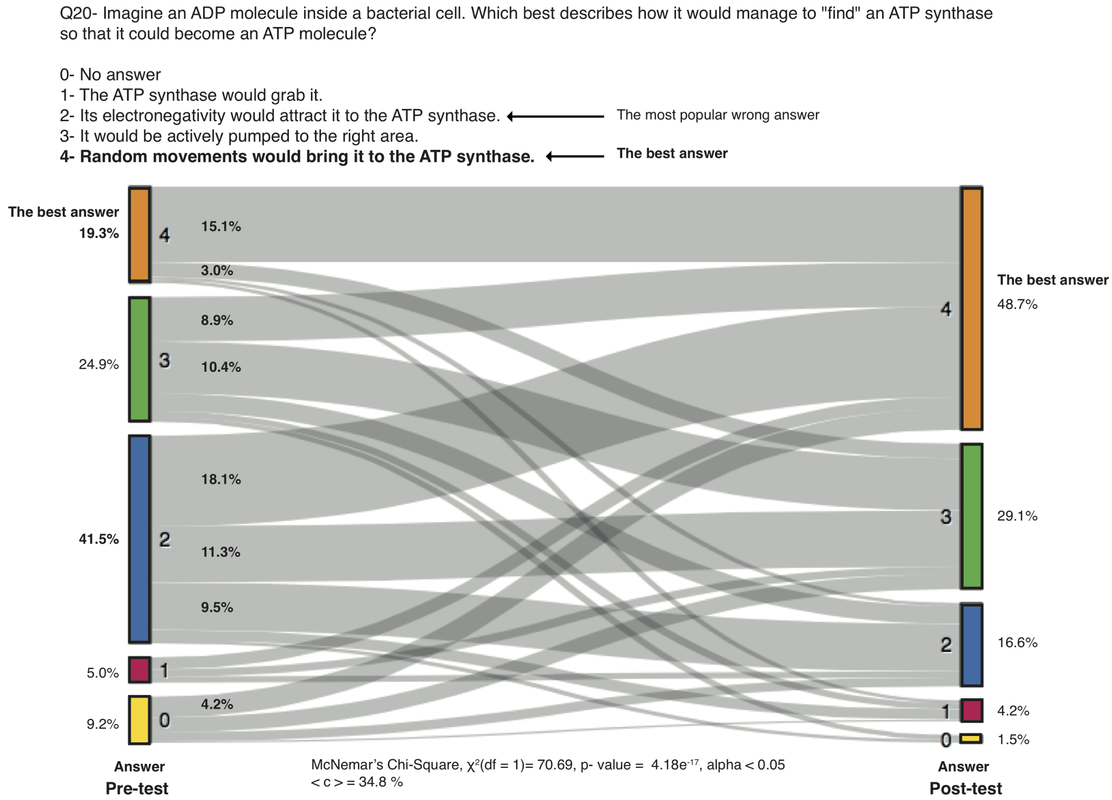
a

Figure 2



b

Figure 3



c

Figure Legend

Figure 1.

The key and lock analogy of molecular interactions is still prevalent after 3 semesters of biology instruction. The flowchart shows how students' answers change from the pre-test (left), at the beginning of the first semester studying biology, to the post-test (right), three semesters later [2].

Figure 2.

Random molecular collisions are not recognized as the major source of breaking molecular interactions. The best answer (2) reflects the fact that molecules interact and dissociate from one another in response to the transfer of energy, typically by collisions with other molecules, sufficient to overcome their interaction energy.

Figure 3.

Stochasticity and randomness are neglected concepts in student's understanding of molecular interactions. In the post-test, half of students still select active processes (answers 1, 2, 3) to explain movement of molecules instead of random diffusion (the best answer is 4).

Results & Discussion

Overall, students demonstrated disappointingly modest improvements on many BCI questions (see Fig. S1 and the BCI answering file in Suppl. Data). Our concern is the students' weak understanding of molecular interactions, which leads to a naive understanding of concepts like diffusion or energetic properties of molecules.

The students' BCI scores were analyzed using the pairwise Wilcoxon test. There were no significant differences between the individual pre-test and post-test scores of the two cohorts (Kruskal-Wallis test, $\chi^2(df = 1)_{pretest} = 0.23$, $p_{pretest} = 0.63$; $\chi^2(df = 1)_{posttest} = 2.24$, $p_{posttest} = 0.13$, alpha <0.05). The scores of students from the two universities were pooled together into single pre- and post-test groups.

As a first example, the question (Q15) asks: "How does a molecule bind to its correct partner and avoid "incorrect" interactions?" (Fig. 1). In the pre-test, 62% of students think that molecules bind perfectly, like puzzle pieces (answer 4), while the best answer was that correctly interacting molecules have a lower (negative) interaction energy (answer 3). In the post-test, ~59% of students selected the best answer. The scores of the pre-test and post-test were significantly different (McNemar, $\chi^2(df = 1) = 60.98$, p-value = 5.77e-15, alpha <0.05), and an intermediate normalized change was calculated (41%) [12] [13]. Consequently, for ~40% of participants, the limitations of analogies need to be clearly articulated in terms of energetic properties [4]. The schematization of abstract phenomena is essential for analogical reasoning [14]. However, what a student takes away from an analogy may not correspond to, or might even conflict with, the instructional purpose of it [14].

Only few students, before or after instruction, appreciate the fact that the dissociation of a molecular complex is driven by random molecular collisions with surrounding molecules (Fig. 2). For example, on this question (Q16), "Once two molecules bind to one another, how could they come back apart again?," there was no significant difference between the pre- and the post-test scores (McNemar, $\chi^2(df = 1) = 0.36$, $p = 0.55$, alpha <0.05). In the post-test, even more students, namely 73%, have selected the wrong answer ("A chemical reaction must change the structure of one of the molecules"). This misconception may be caused by presenting students with reaction models in which reactants bind and products dissociate from a catalytic (enzymatic) complex without emphasizing the role of molecular movements and collisions for substrate binding and release.

We were wondering how biology textbooks used in the introductory biology courses of two Swiss universities use analogies to explain the characteristics or behavior of molecules. In fact, authors often present analogies like the key and lock model, the hand in a glove, or ball and stick representations or the drunken walk when illustrating molecular structures or interactions. Even though those similes may help students to visualize microscopic properties of molecules, the energetic properties on a molecular level and the stochasticity are not explicitly considered. The fact that molecules do not only interact with its specific partner but rather with a range of partners is not easily reconciled with this perspective (one reason that drugs have "non-specific" side effects [15]). Thus, the question remains whether instructors use analogies to explain molecular interactions and whether they explicitly discuss their inherent limitations [4].

We examined lesson plans and slide presentations of introductory biology courses, revealing that the role of randomness in biological mechanisms is only superficially taught, if considered at all. As an example, the drivers of molecular motion (diffusion) and molecular dissociation associated with thermal random motion are not mentioned or stressed as universal features of molecular systems. Our participants were not attracted by answers related to the concept of randomness on the majority of BCI questions. For example, a question (Q20) asks: "Imagine an ADP molecule inside a bacterial cell. Which best describes how it would manage to "find" an ATP synthase so that it could become an ATP molecule?". In the pre-test, ~70% of students selected one of the three distractors, all of which represent "active" driver processes; ~42% selected "active processes like electronegativity of molecules" (answer 2); while 25% selected "active pumping" (answer 3) rather than the best answer that "random movements bring the molecule to the ATP synthase" (answer 4). The improvement from the pre- to the post-test was significant (McNemar, $\chi^2(df = 1) = 70.69$, $p = 4.18e-17$, alpha <0.05) and the normalized learning change was equal to ~35%, corresponding to an intermediate change. In the post-test, still approximately 50% of students select active processes to explain the movement of molecules. The ubiquity of stochastic processes at the molecular level appears to be in conflict with our tendency towards a teleological thinking, which means seeing active purposeful processes of molecular motions [16] [17]. The kinetic properties of molecules and the stochasticity of biological processes are, at best, superficially explained to first- and second-year undergraduates, and based on our observations, current teaching does not result in students clearly recognizing or understanding stochastic biological processes.

Understanding molecular interactions requires fundamental knowledge of chemistry

and physics [18]. The interdisciplinary nature of these concepts is rarely explicitly presented to students studying in a biology curriculum at university [19]. Despite the fact that the first two years studying biology are commonly devoted to learning fundamental knowledge of chemistry, physics, and biology, our results indicate that most of our participants do not appear to develop an appropriate interdisciplinary approach to processes on a molecular level. We suspect that disciplinary silo teaching (not referring to processes and phenomena in other disciplines) is likely responsible for students' weak ability to apply cross-disciplinary thinking. While we often expect that students automatically transfer knowledge from one discipline or domain to another and develop scientific literacy abilities, this appears not to be the case [20] [21].
The questions of the BCI were developed based on the biological thinking of a group of American students [22]. Interviews with these students revealed that many are using analogies to explain their understanding and demonstrated some teleological thinking on how biological mechanisms should or must work. Consequently, many distractors of the BCI questions represent common misunderstandings. Our results on the BCI demonstrated that many students of two first-rate Swiss universities select these distractors and so are likely to share the same misconceptions concerning molecular interactions. It would appear that, regardless of different educational systems, some biological misconceptions are universal.

Conclusions

This project is a first step towards an educational reform in teaching biology at the undergraduate level in Switzerland. Taking advantage of results obtained using the BCI, we were able to diagnose the prevalence and persistence of common misconceptions held by many students. Thus, we provide evidence that such misunderstanding should be addressed in class. The information raised from that project may catalyze some reforms in biology curricula, which should be built to encourage students to develop a better conceptual understanding of biology.

Limitations

Concept inventories diagnose students' misconceptions by their attraction to the distractors, which are constructed based on common naive ideas of students. Thus, one limitation is the attractiveness of BCI distractors. Indeed, if the distractors are not corresponding to students' thinking or the wording does not appeal to them, they might select the best answer only by a process of elimination. Consequently, selecting the best answer does not mean that students really understand. All concept inventories are confronted by this limit. To counteract this possibility, interviews or short-ended questions (the Biological Thinking Survey, manuscript in preparation) are suggested to confirm student's understanding. In addition, the distractors may be attractive differently to students studying in different educational systems as in US and Switzerland. Indeed, the biological thinking a group of American students revealed by doing interviews with them was used to develop questions and distractors of the BCI [1]. Interestingly, many of our participants in Switzerland selected these distractors and so are likely to share the same misconceptions concerning molecular interactions. It would appear that, regardless of different educational systems, some biological misconceptions are universal. The large diversity of concepts investigated in a certain restricted number of questions limits achieving a deeper analysis of specific concepts. The BCI gives insights of the general students' biological thinking on diverse concepts and can be completed by using specialized concept inventories or student interviews/surveys.
It would be interesting to deepen students' biological thinking by interviewing them or by distributing a survey.

Additional Information

Methods and Supplementary Material

Please see https://sciencematters.io/articles/201606000010.

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Ethics Statement

Not applicable.

This manuscript has not been published and is not under consideration for publication elsewhere. We wish to confirm that there are no known conflicts of interest with the publication. The manuscript has been read and approved by all named authors.

Citations

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