Fostering Generative Reasoning about Complex Phenomena in Genetics

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Abstract: The notion of systems is an important idea in science and science education. Genetic phenomena, in particular the mechanisms that link genes to their observable effects, are examples of complicated multileveled systems that students find difficult to understand. Developing generative understanding of the mechanisms underlying genetic phenomena is a critical aspect of scientific literacy in this domain. Here, I describe the design and evaluation of a high school genetics unit aimed at fostering such understandings.

Introduction

The notion of systems is an important and pervading idea in both science and science education (AAAS, 1989). Genetic phenomena and the mechanisms that link genes (genotype) to their observable effects (phenotype), such as eye color or the symptoms of a genetic disorder, are examples of complicated multileveled systems that students find difficult to understand (Horwitz, 1996; Marbach-Ad, 2001; Venville & Treagust, 1998). Understanding the mechanisms involved in genetic phenomena is critical for scientific literacy and the ability to make informed decisions about personal and public issues concerning genetics (Lewis & Wood-Robinson, 2000). Moreover, such understandings need to be generative in nature to allow students to reason about novel and unfamiliar genetic phenomena they may encounter in the future. Fostering the development of generative thinking in genetics entails an understanding of what sorts of knowledge are critical for such reasoning. In earlier work I presented a cognitive model of reasoning in genetics that highlighted essential knowledge forms that undergraduate students employed to successfully reason about genetic phenomena in both novel and familiar contexts. This cognitive model informed the design of a high school curricular unit aimed at fostering generative understandings in genetics. In this poster I discuss the key elements of the instructional design and findings from the implementation of the curriculum in a high school biology classroom.

The Instructional Design

Scientific literacy in genetics involves understanding how the genetic information brings about observable features (phenotype) such as our physical traits, symptoms of genetic disorders, etc. In this regard it is crucially important that students understand that there is an extensive causal chain linking genes to their phenotypical effects and that genes do not directly specify the features as we see them. That is, genes do not directly determine the color of the eye rather they determine the properties of entities whose interactions result in eye color. This is a subtle but critical understanding since it foregrounds the underlying causal mechanism. In my prior work I identified several conceptual understandings that were particularly powerful for reasoning about the genetic causal mechanisms: 1) the understandings that genes directly specify only the structure of proteins, 2) the understanding that proteins are thus central entities in the causal mechanisms of genetic phenomena, 3) knowledge of important and common roles proteins play in those mechanisms, and 4) the understanding that explanations in genetics entail accounting for the complete mechanism (across all biological organization levels) linking genotype and phenotype. Our design team, composed of four biology high school teachers and myself, adopted the four key understandings described above as the learning objectives for the unit.

We employed several design strategies to scaffold student learning of these ideas. In order to help students develop an understanding of the central role and multiple functions that proteins have in genetic phenomena we focused the unit on a detailed investigation of the biological mechanisms underlying a single genetic disorder - Familiar Hypercholesterolemia (FH). In their investigations students compare data from eight cases of patients with FH and four cases of healthy individuals, to uncover the underlying causes of the disorder. Students begin the exploration at the organism level examining the observable effects (symptoms) of the FH gene and through a cyclical process of sequentially delving into lower organization levels (organs, tissues, cells, and proteins) they uncover the complete biophysical mechanism. The major feature of this approach is that it emphasizes mechanisms and much of the time is devoted to exploring the role of proteins in those mechanisms. At this stage students do not

discuss how the genetic information is mapped onto the physical mechanism, rather the focus is on the mechanism itself. To help students understand that the genetic information only specifies the structure of proteins we introduce genes only after students have uncovered the cellular and molecular mechanisms involved in FH. Once most of the underlying causal mechanism has been accounted for the only role left for genes is to specify the structure of proteins; thus motivating the need for information only at the protein level. In this part of the unit students explore the way in which the genetic code determines the structure of proteins, and how changes to that code (mutations) alter the structure and resulting function of proteins. To reinforce students understanding of the nature of explanations in genetics we ask them to create a comprehensive account of the biological basis of FH as the consequential task for the FH investigation. Students write a letter to an assigned case patient explaining the underlying causes of the disorder by providing an account of the mechanisms at each organization level (gene, protein, cell, tissue, organ/organism). This task emphasizes the nature of explanations in the domain and builds on students' experiences in the preceding activities. Again, the focus is on mechanism, the role of proteins, and the mapping between the genetic information and the physical causal mechanism. To further facilitate generalization and application of the knowledge students acquired, the final set of activities in the unit entails compiling information about the biological mechanisms involved in three additional genetic disorders (the information is provided in a set of readings) and creating a complete and coherent account of the biological basis for those disorders. This unit was implemented in an honors 8th and regular 9th grade biology classroom in a Chicago public high school. In the following sections I briefly describe some of the key findings from that study.

Methods

To determine students' understanding of the target concepts identified in the curriculum, as well as students' ability to reason generatively about problems and phenomena in genetics, I conducted qualitative and quantitative analyses of several data sources: pre and post written assessments (n=100); pre and post clinical interviews (n=11), video of classroom instruction, and artifacts of student work (the consequential task). Interviews and written assessments were administered prior to and following the instruction period (5 weeks). Interview tasks focused on eliciting students understandings of the mechanisms underlying genetic phenomena, whereas, the written assessments focused mainly on their understandings of entities and relationships. Artifact analysis ascertained the completeness and connectedness of students' accounts of the causal mechanism of FH.

Results and Discussion

Overall my findings suggest that the curriculum was successful in supporting students' learning of the target objectives. As a result of instruction students developed more sophisticated understandings of genetic phenomena and the underlying mechanisms and were able to reason generatively about novel phenomena and generate plausible and domain-appropriate explanations. Specifically, analysis of the written assessments showed that 68% of students' responses post instruction indicted an understanding that genes code for proteins (versus 1% pre instruction). Moreover, after instruction the majority (64%) of the students were cognizant of the central role proteins play in genetic phenomena and were able to identify proteins as a key link between genes and their effects (4% pre instruction). Analysis of students' explanations of the biological basis of FH showed that the majority (68%) of students' explanations accounted for all five organization levels (genes, proteins, cells, tissues, organ/organism). These explanations not only referred to the different organization levels, but most of them also connected the levels by inferring the causal relationships between them- i.e. how changes at one level (mutation in the gene) would affect subsequent levels (change to a protein and subsequently the cell, etc). That it, most of students' explanations (78%) made 6 or more connections (out of a possible 8) between levels, creating a complete and coherent account of the underlying causal mechanism.

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