

Designing Representations in Deeply Disciplinary Educational Games

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Abstract: Educational games are common in classrooms and have been extensively studied in multiple domains. The *Geniventure* game was developed to support student learning of core concepts in genetics via challenges that engage students with genetic phenomena at the molecular level. A core feature of the game is that it simulates behavior of molecular entities (genes, proteins, organelles) with high disciplinary fidelity to how these mechanisms really operate in the cell. In this sense, it is deeply disciplinary. The commitment to disciplinary fidelity presents design challenges regarding the ways in which entities, activities, and mechanisms are represented and manipulated in the game across the biological organization levels. We discuss five distinct types of design challenges that we identified based on data from focus groups with students who played the game and provide design heuristics for addressing these challenges.

Introduction

The development and research on educational games has increased substantially in the past decade (for recent reviews see Clark, Tanner-Smith, & Killingsworth, 2016; Ravyse, Blignaut, Leendertz, & Woolner, 2017). This work has identified key features that make games more engaging and productive for learning such as having them be pleasantly frustrating, involving well-ordered problems, and providing the player with agency, to name a few (Gee, 2005). This research has also provided some guidelines for the design of successful educational games (e.g. Kafai, 2006; Winn, 2009).

In addition to these critical aspects of game design, we wish to draw attention to considerations of designing *deeply disciplinary* games and in particular designing representations of key disciplinary entities and processes in these games. We use the term *deeply disciplinary* to refer to games that aim to engage students with key disciplinary phenomena and in which the game play involves manipulating entities and mechanisms within these phenomena that may be unfamiliar to students. This construct draws on the notion of *conceptually integrated* games, which integrate domain concepts and relationships into the core mechanics and representations of the game (e.g. Habgood & Ainsworth, 2011) and expands it to include a stronger emphasis on the representation of domain-specific entities and mechanisms in ways that maintain high fidelity to the structure, function, and interactions of these entities. For example, the game *Geniventure* engages students in the genetic study of drakes, the model organism for dragons; students directly manipulate chromosomes, genes, and proteins in order to change the drakes' traits. The representations of these genetic entities in the game are therefore a central component of making the phenomena accessible on the one hand, while maintaining fidelity to the disciplinary entities represented on the other. The tension between accessibility of the representations and their disciplinary fidelity generates interesting challenges in terms of design decisions regarding the representations and the linking of representations across the multiple user interfaces of the game.

Research on students' understanding of disciplinary inscriptions (such as graphs, models, equations) provides some insights that can help inform these design decisions. For example, zoom-in features, alternative perspectives, and control of speed of animations/simulations can help facilitate perception and comprehension of important disciplinary entities and processes (Tversky, Bauer Morrison, & Betrancour, 2002). Similarly, tighter coordination and coherence between multiple representations (especially when visualizing phenomena at the macro and molecular levels) is also important to reducing cognitive load and helping students make appropriate connections (Kozma, 2003). In addition, it is often difficult to provide, within the representations, all the needed conceptual and social resources that can help convey the utility and purpose of disciplinary representations/inscriptions (Roth & Bowen, 1999). However, much of this research was conducted in the context of students using and creating inscriptions within, mostly traditional, instructional pedagogies such as the use of inscriptions, animations, or simulations to explain a science concept. Moreover, the research on using computerized models for understanding molecular-level representations and ideas predominantly comes from chemistry (Barnea & Dori, 1996; Williamson & Abraham, 1995; Wu et al., 2000), whereas only a few studies deal specifically with molecular biology (e.g. Pallant & Tinker, 2004; Tsui & Treagust, 2004). Therefore, while

relevant, this body of work does not address the specific challenges associated with using disciplinary representations in game contexts, which are not as conducive to traditional ways of scaffolding and providing information. In such environments, engagement with disciplinary representations and phenomena is in the context of a game challenge and students figure out the key ideas through game play. Exiting the game play to “instruct” or explain the representations or processes can be distracting and problematic in terms of motivation.

Here we present findings regarding middle school students’ understandings of representations and processes in a genetics game and their implications for the design of representations in deeply disciplinary games. The online game, *Geniventure*, is a fictional and narrative-based game in which students are enlisted to help breed dragons with traits that can help them in the struggle against a nearby kingdom’s attacks. As the game opens, students find themselves inside the Mission Control room of a secret underground headquarters for dragon development and breeding. A diverse cast of characters presents students with a series of challenges that address a need for specific traits and an understanding of how those traits are achieved via genetic instructions. Students “travel” to different rooms in the underground compound to breed drakes, manipulate genes, or zoom into cell simulations to interact directly with proteins and DNA. Student actions in a challenge are tracked and upon completion of a challenge students are awarded “crystals” based on how well they performed the task.

The game is designed to help students develop core understandings in genetics including patterns of inheritance (alleles on paired chromosomes control each trait), how random assortment of chromosomes into sex cells results in the observed probabilities of the expression of traits, and how genes on those chromosomes code for proteins that bring about those traits. In this article, we focus predominantly on the game challenges involving proteins (described in more detail below). We conducted focus group interviews with three groups of students who played the protein challenges with the aim of finding out how they understood the nature and role of proteins in mediating the genetic traits involved in the challenges. Our research question is: how are students interpreting and responding to the different representations of molecular entities, mechanisms, and levels of the phenomena (genes, protein, cell, trait) embodied in the game? We next describe the online game, *Geniventure*, and some of the key design decisions that were made in developing the representations of the phenomena.

The Geniventure game: Protein challenges

The protein challenges are designed to engage students with the mechanisms that connect genes and traits. Genes are DNA sequences that specify instructions to the cell for building protein molecules. Proteins are the workhorses of the cell; they have many different functions, and their functions are closely tied to their structure. Seemingly small differences in the DNA sequences of genes can have profound effects on an encoded protein’s structure and in turn on its function. Different versions of a gene, called alleles, produce different traits by virtue of these differences in the structure and function of the proteins they encode. Thus, proteins are an essential link for productive reasoning about how genes confer traits on individuals.

Proteins are often characterized by experts as molecular machines (e.g., Goodsell, 2009). This is a useful analogy since students understand that machines have functions, and that the form or shape of a machine is essential to its function. In designing the look and feel of proteins in the game, we chose to emphasize their machine-like qualities by using simple machine structures like gears, and we designed their shapes to match



Figure 1. The size challenge.

very obviously with their function. We used color gradients and softened edges to convey their biological nature; influenced by Goodsell's (2009) use of color in illustrating actual protein structures.

The protein mechanisms we targeted in the game are situated in drake scale cells (analogous to human and other animal's skin cells) and focus on the production and transport of melanin. We chose drake color as a trait for our protein focus because it is a readily discernable trait and it is constantly and actively maintained by cells through protein-based mechanisms. In the game, students are exposed to the proteins "doing their jobs" and then are given the opportunity to either interfere with what the proteins are doing or to help them along the way, all with the goal of changing the color that the cell produces. The melanosome organelle stores melanin and changes in color based on how much melanin is present. In the game, there are two types of challenges that involve proteins. In the first, which we call the "size" challenge, students try to create smaller or bigger melanosomes. We have reduced the complexity of the mechanism to consist of two proteins, both of which are active in real organisms. One is an enzyme that synthesizes melanin, represented in the game by a set of gears that can assemble melanin, and its "helper protein" that provides stability to the gear enzyme, represented by a shaft that holds the gears together (see Figure 1). The proteins build melanin, which is represented as stars, by assembling the triangular building blocks (white triangles) into melanin stars. Melanosomes change color from orange to gray depending on how many melanin stars are in them; bigger melanosomes are darker gray and smaller melanosomes appear orange. Students work through several instantiations of the size challenge in which they have to either reduce the size of the melanosome (to make an orange drake) by breaking the melanin stars and slowing down the gears, or increase the size of the melanosomes (to make a gray drake) by helping to assemble the gear-shaft complex so it works faster to make melanin stars and thereby grow the melanosome.

In the second challenge, which we call the "gates" challenge, students try to create shiny versus dull/matte drakes (that can be either orange or gray). Shininess (or sheen) is a function of not having any color (no melanosomes) in the outer layer of scale cells, causing those cells to better reflect light and making the scales look shiny. Melanosomes can travel to the outer scale layer through gated channels. These channels are plugged by a protein that selectively lets melanosomes through. The protein is represented by a corkscrew-like structure with a pink tip that can sense the incoming melanosome (see Figure 2). In shiny drakes, the protein plug is not functioning properly and does not ever open the channel; therefore, no melanosomes can get to the outer layer and the scales are shiny. Making the outer layer of scales actually look shiny in the game was a graphics-design problem, and there did not seem to be a simple way of showing sheen. Therefore, we opted for a different solution—having a *sheen indicator bar* positioned at the top of the field of play, within the outer scale layer. When the indicator is "full" it means there are lots of melanosomes in the outer layer and the scale is non-reflective (matte); when the indicator is empty, the scale is shiny. In this challenge, students are tasked with changing drakes from shiny to matte or vice versa by plugging or unplugging the channels.



Figure 2. The gates challenge.

Both challenges involve students trying to change the color or sheen of the drakes from a provided initial state to a required target state. To help students keep track of their progress (the extent to which the drake is changing) we developed a Heads Up Display (HUD) that includes three elements: a) the initial (start) state of

the drake shown as both a thumbnail of the drake and a thumbnail of a cross-sectional view of the skin tissue; b) the current state of the drake with a thumbnail of the drake only, that actually updates based on progress in the game; and c) the target state shown as dual thumbnails of the drake and cross section of skin. The HUD appears along the right side of the field of play (see Figure 1 & 2) and is present in both challenges.

Methods

Study context

The game was played by $n=51$ middle school students in the context of an eight-week summer program hosted by a community center in a metropolitan city in the North East. The program was open to all middle school students in the city yet the majority of the participating students attended the local public middle school where the program was held. This 6th–8th grade middle school is ethnically diverse: 38% Black, 25% White; 16% Hispanic, 10%, Asian; with 43.4% economically disadvantaged students. The genetics program in which the game was used ran for 90-minute sessions twice per week and was led and instructed by the Middle School Program Leader and STEM Specialist of the community center. One or two researchers were also present during the genetics programming to assist the instructor. Each session was structured to include some hands-on instructional activities in which students explored various aspects of genetics—for example, students built catapults using normal and ‘mutated’ instructions to see how changes to the instructions can result in changes to the catapults shape and function. These activities were often followed by whole class discussions about the biological meaning of the activity and how it relates to genetics. Students typically spent about 30 minutes, on average, playing the online game during these sessions. The protein challenges, which are the focus of this article, occurred in weeks 3–5 of the summer program. We wish to note that due to various logistical challenges, frequent absences of students, and varying level of engagement of students, the instructor and research team were not able to implement the planned curriculum with high fidelity. Thus, some of the activities and resources that were expected to support student understanding during game play were not fully implemented. While this was a general problem for the ongoing research, we feel that the information from the focus groups is still highly valuable in highlighting issues with the game; some of which may be ameliorated through curriculum activities while others likely require revisions to the actual game design.

Data collection and analysis

The focus group interviews occurred in week 4 of the program. Student groups were formed based on the game challenges that the students had completed. Focus groups of students who did not reach the protein challenges were not included in this analysis. A total of 9 students participated in the three focus groups included in our analysis. The focus group interview lasted between 19–26 min and involved showing students screenshots of interfaces in the protein game and asking them questions about specific entities or processes occurring in those interfaces such as: “how close is the person playing the game to winning?” “what would you do to make the dragon darker?” “what would you click on next?”. Students took turns answering each question and the interviewer made sure none of the students had anything else to add to the discussion before moving on to the next question. Focus group interviews were transcribed verbatim and analyzed by the research team (authors).

Analysis involved viewing the videotapes together and identifying episodes of interest (e.g. students misunderstanding a representation, students explicitly expressing confusion, etc.). While we cannot claim to have identified all potential problems with the game, and in some cases only one student in the group struggled with a particular issue, we can assume that if these issues happened once, they may happen again. Therefore, we describe the issues that came up without making claims about their prevalence among student players. We grouped the issues we identified under five themes that we see as being potentially relevant for game design in other contexts and discuss them in the results section. We then offer some heuristics for designing representations for deeply disciplinary games that could help address the general problems we identified.

Results

Before we discuss specific themes of problems with the game we wish to note that overall the students did seem to interpret representations, game phenomena, and game play as intended by the designers. Many of the features that we had hoped they would notice about the representations of genes, proteins, and traits in the game were indeed attended to by the students. It was also clear that students who had more prior knowledge in genetics, which came through in the interviews without us explicitly asking questions about genetic concepts, understood the game phenomena, mechanisms, and entities better than students who did not. This is not surprising and has been documented extensively in prior research (Cook, Wiebe, & Carter, 2007; Kindfield, 1994).

The five thematic problems we identified are: (1) incongruence between phenomenological knowledge and representations, (2) unintended distractors, (3) non-salient ontological distinctions, (4) misinterpretation of linked representations, and (5) confusing game progress and disciplinary process indicators. We discuss them in turn, by first describing the problem as it arose in the focus groups, then providing our interpretation of what is the specific problem is a case of, and lastly discussing some possible solutions for this problem in the game.

Theme I: Incongruence between phenomenological knowledge and representations

As we noted earlier, the building blocks of melanin (white triangles) can be assembled into melanin “stars”, which are initially light orange. As they accumulate, however, they become darker—as does the overall melanosome (Figure 1). In one of the initial challenges, students are tasked with making a darker gray drake by interacting with the process of melanin star production in the melanosomes of a lighter orange drake. One of the students in the focus groups noted a confusion he initially had when playing this challenge. He assumed that *breaking* the bright orange stars would lead to darker melanosomes. We interpret this situation as the student drawing on phenomenological primitive-like knowledge (diSessa, 1998) of the sort- “less bright means dark” and acting on it to break apart (remove) the bright-looking stars. While the student eventually recognized that the strategy of breaking stars had the opposite effect (smaller melanosome), the student’s initial interpretation of the representation (bright stars) and its relation to the phenomenon (skin color of drake) is important. This is because the student’s initial reaction was intuitive and yet counterproductive given the specific representations used. We argue that in general terms this is a problem of having representations and/or processes that behave in ways that counter, or are incongruent with, students’ phenomenological knowledge. By this we do not mean that the representations are complex or unfamiliar, or that the processes are counterintuitive. Rather we mean that the actual choice of color (or other feature) of the representation, from a semiotic perspective, is incongruent with students’ knowledge of how entities behave in the world at a basic phenomenological level. The decision to make the stars light orange on a dark blue background was driven by the aesthetics of having the stars stand out as brighter objects on the screen. In hindsight, this was problematic in that it cued students to take an intuitive but unproductive action. Fortunately, the problem also has a fairly simple solution of changing the background color of the field of play to a lighter color such that the stars are not so bright that they appear to generate light.

Theme II: Unintended distractors

Research has shown that students, especially those with low prior knowledge, tend to select the most noticeable features of the representations for further processing and may ascribe meaning to un-important features of representations when mapping between macro and molecular representations (Cook, Weibe, & Carter, 2007; Seufert, 2003). While we found that students did notice most of the relevant details of entities and processes in the game, they also noticed and attempted to interpret details that were not relevant. For instance, in the melanosome size challenges, when a melanosome is small the triangular building blocks of melanin tend to cluster in a higher concentration around the melanosome; when the melanosome is larger the same number of triangles are still there but seem less concentrated due to the larger circumference of the melanosome. This is a randomly occurring situation that is an artifact and not a feature of the representation. However, one student assumed that the discernable clustering of triangles around the melanosomes as somehow contributing to the change in melanosome color. In general terms, this is a problem of unintended (unforeseen) and sometimes unavoidable distractors in a complex disciplinary display of mechanisms. The clustering of triangles, while not a designed behavior per se, is nonetheless reflecting the real-world complexity of the mechanisms and the random nature of particle movement in the cell. A solution therefore cannot be to avoid this occurrence. The point we wish to make is that student will attend to all features of the representation, those that were deliberately engineered as well as those that were not (and are meaningless). Our solution here will be to try and alter the underlying dynamics of the representation such that the clustering behavior is less frequent.

Theme III: Non-salient ontological distinctions

In the game, there are several distinct kinds of entities such as proteins, their substrates (triangles) and their products (stars). As noted above, we used representational elements that resemble little machines to convey the functional aspect of proteins (as molecular machines that carry out functions in the cell). In contrast, we used simpler geometrical shapes to represent protein substrates and products. Our attempts to convey this ontological distinction through semiotic cues were not always interpreted as intended by students. While students did notice the more complex and gear-like shapes of proteins, they did not view these as inherently different kinds of things from the stars and triangles, and did not realize the biological significance of the differences. One might argue that this is not surprising given that students lacked prior knowledge in the domain and therefore were unlikely to understand the biological meaning of the differences in representations. We agree that students’

domain knowledge plays a role here, however, if the game is intended to help novices learn about the biological significance of key entities and mechanisms in genetics then finding ways to convey important ontological distinctions in the discipline is an important user interface design goal. It is not clear to us how we can necessarily improve the representations in order to make the meaning of the distinctions more salient. The solution to this problem will likely involve adding information to the game through hints or other cues that help students make sense of the differences they are already noticing in the representations of entities. Or it may be that the sense making needs to occur in the context of group/class discussion in which the teacher facilitates student reflection on the differences and what they mean.

Theme IV: Misinterpretation of linked representations (HUD)

A central representational feature in the protein challenges is the HUD, which provides real-time information about the current color of the drake relative to the initial state of the challenge and the target state. The HUD provides representations both at the cell level, using a cross sectional skin tissue view, and at the whole organism level by displaying a thumbnail of the drake (see Figure 1). The “current state” cell and drake representations in the HUD are linked to the field of play. We identified two representational problems with the HUD design. First, some students did not understand that the centered part of the HUD was representing current state. They instead thought it was representing an intermediate state between the initial and target states and therefore when shown a screenshot including the HUD, they struggled to determine how far along the player was on that particular challenge. This type of confusion of the HUD was surprising to us given the central role the HUD plays in helping the players determine their progress in the challenge.

The second problem with the HUD related to the specific representations chosen to portray the cell/tissue levels, and was more severe for the “gates” challenges than for the “size” challenges. In part, this relates to the complexity of the phenomenon in each challenge. The gates challenges entail understanding that melanosomes move (or are blocked from moving) from one layer of cells in the skin into another, more surface layer. The ideas that skin is multilayered and that organelles like melanosomes can travel between cells were likely new to students, and while they could successfully play the challenge it was clear that many did not understand the underlying biological phenomenon. The HUD in this case was particularly confusing because it provided a cross section of the two layers of cells. Students were able, for the most part, to interpret their state in the game using the HUD but could not explain what the representations in the HUD were actually showing (i.e. where is this in the drake?). We believe that students may be unfamiliar with cross sectional images and how to relate them to a “view from above” perspective. While they could pattern-match entities in the field of play to their smaller representations in the HUD, they did not understand how the zoomed-out view of the HUD is spatially oriented in relation to the representations on the field of play. Stated in general terms this is a problem of both misinterpreting the linked representations and being unfamiliar with particular disciplinary inscriptions. A solution to this problem could be to change the representation used in the HUD from a cross section view to some other more familiar view. However, the cross-sectional view is a fairly prevalent disciplinary way of showing locations of cells within a larger organismal context and there are reasons to keep it given the work it can do (when someone understands it). If the representation remains, the solution to this problem will likely entail providing more cues about the relationships between the spatial orientation of the HUD and the field of play. Perhaps adding a short video that shows how you get from one perspective to another (at the start of the gate challenges) will allow students to “see” the connections between these linked representations.

Theme V: Confusing game progress and disciplinary process indicators

In the gates challenges, students try to change the sheen of the scales of the dragon from matte to shiny or vice versa. As noted earlier figuring out how to represent an increase or decrease in scale sheen in the game was a design challenge that we opted to solve by incorporating an indicator bar for sheen that shows how shiny the outer cell layer is at any point in time (an empty bar means the scales are shiny and a full bar means the scales are matte). The sheen indicator bar sits within the field of play (see Figure 2) and includes a small indicator arrow that shows the target state (empty or full bar). The location of the sheen indicator bar compounded with the complexity of the mechanism of the phenomena (students struggled to understand why it is that having no melanosomes in the outer cell layer makes a dragon shiny) resulted in some confusion about what that bar was actually representing. Some students understood it as showing sheen (as intended), while others thought it showed progress in the challenge (like the HUD). In the latter case, this was a problem when the target dragon was shiny and the goal was to have an empty bar. The discrepancy between the bar being empty and the challenge being successfully completed was confusing to some students who expected a full bar to indicate the challenge was complete. In general terms, the problem here is one of inconsistent use of general game navigation cues (like a progress bar) to represent mechanistic processes of a disciplinary phenomenon. Overall

using a progress-bar type representation to show changes in a mechanism is not an issue in and of itself; in fact, the HUD provides such support in the protein challenges. The case here is that this was a new navigational/indicator feature that was used sporadically in *only* one set of challenges- the protein gates challenges. One possible solution, therefore, is to either include a similar indicator bar in the other challenges or to try again to figure out how to represent sheen within the phenomenon itself (in the outer layer of cells).

Discussion

The focus group interviews, while limited in scope, nonetheless provided us with valuable information about the ways in which students attended to, interpreted, and acted on the representations of phenomena in the game. The problems we identified reflected design and usability challenges associated with representing entities and mechanisms that are inherent and endemic to the discipline of genetics. In this section, we wish to ‘pop up a level’ and discuss some of the implications from this work more generally and provide a set of heuristics that can guide the design of representations in deeply disciplinary games.

The first heuristic, *balancing aesthetics, disciplinary fidelity, and phenomenological congruence*, stems from themes I and II. Deeply disciplinary games need to maintain high fidelity to the discipline in terms of how entities, activities, processes, and so on are represented. They also need to engage and attract students, and whenever possible they should be consistent with phenomena and behaviors that students may be familiar with (e.g. correspond p-prims that students likely hold). Balancing these three demands is not trivial and decisions that privilege aesthetics over fidelity or congruence (intentionally or not) could be costly in that it may take students longer to figure out the game dynamics. In addition, while disciplinary fidelity may seem like the most important consideration, adhering to it may have inadvertent consequences if it leads to meaningless aspects of a mechanism or entity being overly salient (e.g. clustering of triangles around the melanosome, Figure 1). It may be prudent at times to forgo some of the fidelity in favor of avoiding such situations.

The second heuristic, *pointing out core disciplinary distinctions*, stems from theme III. We have found that students were able to notice differences between ontologically distinct entities, but they did not recognize the biological significance of these differences. Altering the representations to make them even more different from each other, and different in ways that better reflect their ontological origins, may minimize the problem to some extent. Yet such changes are unlikely to be enough and we believe that additional scaffolds are needed to help students grasp the disciplinary nature and significance of the differences. The scaffolding design framework developed by Quintana et al., (2004) included a guideline about *making disciplinary strategies explicit in learners’ interactions with the tool* (p. 345), which addresses the similar problem of students not having disciplinary knowledge to guide them in reasoning about problems in the discipline. The heuristic we provide builds on and extends this guideline by suggesting that one also needs to make explicit *ontological distinctions and features* of core entities and mechanisms. For example, in our game, it will be beneficial to explicitly point out that proteins resemble little machines because they act as such in the cell, whereas the melanin stars are inactive molecules comprised of smaller building blocks. Such “pointing out” needs to be done in the context of the game in ways that do not interrupt the game play. In a sense this conceptually important ontological distinction was not integrated well enough in the game. This presents a true design challenge in terms of making these key distinctions better conceptually integrated into the game. Another potential solution may be to draw on the Constructed Authentic Representations (CAR) principle (Holbert & Wilensky, 2014) and to allow students to build (through manipulation of DNA sequences- the instructions) proteins with particular functional domains. This may make more salient the distinction between what can be constructed (protein machines) by changing the genetic instructions and what is synthesized by using the protein machines.

The third, and final, heuristic, *supporting the linking of phenomena states to progress indicators*, stems from themes IV and V. We found that students had difficulties in relating both the HUD and the sheen indicator bar to the state of affairs in the field of play. There are actually multiple issues that contributed to this problem including lack of disciplinary knowledge of common representations (cross sectional views of tissues), the difficulty in representing sheen, and misinterpreting the indicator bar to be a general progress indicator. Therefore, in designing HUDs one needs to consider what types of links to the phenomenon are represented. Links could be temporal, showing ongoing progress of a mechanism as in the start-current-target states in the HUD; and/or the link can be spatial, showing where the mechanism is occurring in relation to the rest of the phenomenon as in the cross-sectional images of the cell and the images of the drakes in the HUD. In both cases students need support in making the connections and understanding what the HUD is showing. It is likely that the HUD in the protein challenges by itself is insufficient to support this linking and that additional scaffolds may be needed to help orient students to relevant relationships (such as an animation that connects the HUD and the phenomenon).

In designing *Geniventure* to accurately reflect complex genetic phenomena at the molecular level, we made many design decisions regarding how to represent key disciplinary entities and processes in the game in ways that can convey their biological characteristics. In many cases, the decisions proved effective and students were able to comprehend what they are doing in the context of the game and make progress across challenges. In other cases, the decisions hindered student progress. Moreover, even students who were able to progress substantially in the game did not always understand some of the underlying biology, such as the differences between proteins and other molecules in the cell (e.g. melanin). This underscores the importance of providing supporting curriculum and instruction to help students reflect on and generalize the mechanisms they are seeing in the game and their biological significance. A key question that arises is how can we decide on the division of scaffolding labor between the game, curriculum, and instruction (teacher and peers). This issue is even thornier in educational game contexts where there is a risk of making the game feel more school-like in ways that disengage students.

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