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LEARNING

Young students' understanding of the relationship between inheritance and variation of traits using structural equation modeling

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Abstract

Genetics has become increasingly important in everyday life, a fact that is reflected in state and national science education standards. This study examines the relationship between 474 fifth graders' understandings of the core ideas of *inheritance of traits* and *variation of traits*. A confirmatory factor analysis, supplemented with qualitative analyses of students' responses, revealed a relationship between these concepts and contributed evidence about the nature of students' challenges in learning these ideas. While most students demonstrated some normative ideas, many struggled to explain *variation of traits* as resulting from equal inheritance of genetic information from two parents. Instead, they focused on generational patterns of visible traits or on the influence of nongenetic factors. Deepening understanding of young students' heredity-related thinking can improve preparation of older students for learning advanced genetics-related ideas.

KEYWORDS

inheritance of traits, knowledge integration, structural equation modeling, variation of traits, young students

1 | INTRODUCTION

Genetics is an increasingly important topic in today's society and can vary in how it is defined. Wikipedia defines genetics as "the study of genes, genetic variation, and heredity in living organisms." In issues ranging from the consumption of genetically modified foods to testing one's genetic predisposition to certain diseases, understanding principles of genetics plays a vital role in everyday health-related decision making (Costa-Font, Gil, & Traill, 2008; Kesselheim, Cook-Deegan, Winickoff, & Mello, 2013; Stark & Pompei, 2010). Relatedly, information on one's personal genome is becoming more accessible to patients and physicians, and the impact of this genetics-related information on patients' health is undeniable (Feero, Guttmacher, & Collins, 2008; Schloss, 2008). Our society is moving toward the goal of using genetic information to assist everyday people in making health choices, rendering their understanding of that information ever more crucial. In the United States, the *Framework for K-12 Science Education* (2012) developed by the National Research Council (NRC) of the National Academy of Sciences, includes health decisions when discussing the importance of students developing a deep understanding of science. Other reasons cited by the NRC for deepening our understanding of science topics, including genetics, are keeping a competitive workforce in science, technology, and engineering as well as using this knowledge in the prevention and treatment of diseases. Furthermore, the authors of the Framework make the point that these decisions exist outside the realm of careers in science, thus making this understanding of science topics such as genetics relevant for all students regardless of their future career path.

Existing research has demonstrated that young students' foundational knowledge of genetics can support their later learning of more advanced concepts (Duncan, Rogat, & Yarden, 2009). However, numerous studies have shown that these ideas are difficult for students to grasp at all ages (e.g., Ayuso & Banet, 2002; Duncan & Reiser, 2007; Haga, 2006; Lewis & Kattman, 2004; Lewis & Wood-Robinson, 2000; Tsui & Treagust, 2007, 2010; Venville & Treagust, 1998; Venville, Gribble, & Donovan, 2005; Williams, Montgomery, & Manokore, 2012). For example, younger students have trouble understanding the causes of variation of traits across generations and the ways that equal parental contribution of genetic information influences inheritance of traits (Clough & Wood-Robinson, 1985; Kargbo, Hobbs, & Erickson, 1980; Springer, 1996; Terwogt, Stegge, & Rieffe, 2003). The difficulties experienced by these students may serve to cement their nonnormative ideas, or inaccurate scientific ideas, about genetics. Older students who are building on a shaky foundation of genetics-related understanding may experience difficulty in understanding more advanced concepts. For instance, they can struggle to understand mechanisms occurring at the microscopic level that relate to variation of traits and genetic inheritance through sexual reproduction, such as processes related to meiosis (Banet & Ayuso, 2000).

2 | PROBLEM FRAMING

To prepare students to understand more advanced and complex genetics concepts, U.S. state and national standards indicate that students should be introduced to genetics-related concepts by middle school. In the United States, middle school would refer to grade levels 6–8 (e.g., Michigan Department of Education, 2007; Next Generation Science Standards [NGSS] Lead States, 2013). There is also recent research that suggests the need to include genetics ideas in the curriculum for primary education (Duncan et al., 2009; Venville & Donovan, 2007). Early exposure to genetics ideas also serves the purpose of allowing students to build the prerequisite knowledge needed to be successful in high-school-level biology classes.

Given the complexity of the genetics ideas that students must grasp, it is imperative that researchers develop a deeper understanding of how students assimilate genetics-related ideas when they are first introduced to them (Duncan & Tseng, 2011). Research on students' understanding of genetics is mostly at the middle school and secondary levels (Cisterna, Williams, & Merritt, 2013; Duncan et al., 2009; Venville et al., 2005; Williams, DeBarger, Montgomery, Zhou, & Tate, 2011), with few studies on what genetics-related knowledge younger students have before middle school. To contribute to improving students' foundational genetics knowledge, further studies are needed into how young students, which would include grade levels 3–5, are making sense of and connecting concepts that are relevant to their later understanding of complex genetics ideas.

This paper explores Grade 5 students' conceptions of genetics-related ideas, primarily *inheritance of traits* and *variation of traits*, core ideas outlined in the U.S. NRC Framework (2012). The research questions investigated were as follows:

- How do upper elementary students make connections between ideas related to *inheritance of traits* and those of *variation of traits*?
- What is their ability to integrate knowledge and make scientific connections around these core ideas?

3 | BACKGROUND

To investigate these research questions, it is crucial not only to consider what fifth graders are expected to know according to what the U.S. NRC Framework (2012) outlined about these concepts, but also to learn how they tend to struggle with them, and how these ideas are connected. In this section, we present existing literature on what Grade 5 students should know about *inheritance of traits* and *variation of traits*, as well as on the nonnormative ideas that typically arise in their initial understandings.

3.1 | Students' expected conceptions of *inheritance of traits* and *variation of traits*

Duncan and colleagues (2009) laid out ideas that students should be learning in Grades 5 and 6 as part of a learning progression toward genetics-centered big ideas. This learning progression may be seen as guiding the shift from the more basic upper elementary genetics standards to the more advanced middle school genetics standards. Duncan et al. (2009) argued that fifth-grade students should be learning, among other things, that genes are located in organisms' cells, that genes directly lead to trait development, and that sexual reproduction allows an offspring to be genetically different from its parents because they receive half of their genetic information from each parent. These authors also suggested that a major goal of fifth-grade students' genetics learning should be to connect it to students' existing ideas about kinship and inheritance within families. Moreover, they pointed out that while it would be fitting to develop students' ideas about genetic variation and equal genetic contribution from parents, it would be unnecessary to focus on patterns of inheritance as a major goal of instruction at this grade level.

When discussing elementary students' understandings about the *inheritance of traits* and *variation of traits*, it is important to consider what concepts are grade-level appropriate for young students and what ideas they are generally expected to know. After all, attempts to teach first graders about the basic idea that offspring resemble their parents would be more appropriate than lessons on the detailed, microscopic processes involved in meiosis. For the purposes of this study, we examine the genetics-related learning of students in Grade 5. The U.S. NRC Framework's K–12 Science Education standards lists the core ideas of *inheritance of traits* and *variation of traits* under the third disciplinary area of Life Science (LS) and labels it as "LS 3: Heredity: Inheritance and variation of traits." In the 2013 Next Generation Science Standards (NGSS), which are based on the U.S. NRC Framework's K–12 Science Education standards, Grade 5 is considered part of the Grades 3–5 grade band. Although Duncan et al.'s (2009) set the stage for some of the core ideas around genetics that students in the upper elementary should know, it does differ in what the NGSS Lead States (2013) lays down as expectations by Grade 5. Within this grade band under the NGSS Lead States (2013), students are expected to demonstrate understanding in relation to the core ideas of *inheritance of traits* and *variation of traits* that "plants and animals have traits inherited from parents and that variation of these traits exist in a group of similar organisms" (3-LS3-1, p. 20). The core idea of *inheritance of traits* focuses mostly on students learning that "many characteristics of organisms are inherited from their parents." (NRC, 2012, pp. 158–159). This core idea of *inheritance of traits* is further clarified to connect to the core idea of *variation of traits* through the understanding that "different organisms vary in how they look and function because they have different inherited information" (p. 20). The basic standards in place for upper elementary students with regard to their genetics knowledge are in contrast with the more advanced expectations for students in the next grade span. Thus, developing a strong knowledge of genetics in the elementary grades would form a foundation for students to build upon in their middle school years. For example, by the end of their middle school years (Grades 6–8), students are expected to develop significantly more detailed knowledge about genetics (Duncan et al., 2009). One NGSS Lead States (2013) middle school standard requires the knowledge that genes are "located on chromosomes" and changing them "may affect proteins" (MS-LS3-1, p. 53). This knowledge then connects to the core ideas that "each chromosome pair contain[s] two variants of each of many distinct genes" and that "each distinct gene controls the production of specific proteins, which in turn affects the traits of the individual" (p. 53). Another NGSS Lead States (2013) standard requires students to understand that "sexual reproduction results in offspring with genetic variation" (MS-LS3-2, p. 53), which connects to the ideas that "variations of inherited traits … arise from the genetic differences that result from the subset of chromosomes (and therefore genes) inherited" and that "in sexually reproducing organisms, each parent contributes half of the genes acquired (at random) by the offspring" (p. 53). These are only two of the life science standards for the middle school grades related to genetics, but they are the ones most pertinent to the goals of this paper.

3.2 | Students' nonnormative ideas around *inheritance of traits* and *variation of traits*

Although most of the research around students' ideas about *inheritance of traits* and *variation of traits* has focused on the secondary level, some studies have explored upper elementary students' nonnormative ideas connected with these topics. These studies often have included upper elementary students alongside those in the middle grades. Kargbo and colleagues (1980) interviewed students in all Grades 1–8 about their ideas related to *inheritance of traits* as well as the environmental influence on traits. Terwogt and colleagues (2003) had students from different age-level cohorts (including a group of 10-year-olds) explaining a problem related to parents and offspring resemblance. Venville and colleagues (2005), explored 9- to 15-year-old students' ideas about genes and DNA. Similarly, Smith and Williams (2007) described the ideas of students from different age-level cohorts (including a group of 10-year-olds) about the concept of gene. Cisterna and colleagues (2013) described 10- and 12-year-old students' ideas about cells and heredity through the analysis of embedded assessments in the context of a genetics-focused curriculum.

The above studies provided important insights about what students know about the topics of *inheritance of traits* and *variation of traits* and what challenges students tend to experience. They had in common a cross-sectional design and had the purpose of tracing students' ideas across various ages to examine how those ideas may develop. Most are based on students' tests or on clinical interviews conducted with samples of students, but they generally are not connected with a particular instruction or curriculum designed to teach students about heredity. Contrastingly, two studies were conducted in the context of classroom instruction of these topics. Venville et al. (2005) conducted their study with groups of students from classrooms learning about the inheritance-related topics covered in the Australian national curriculum. As an exploratory study, Cisterna et al. (2013) traced students' progress in online embedded assessments during a curriculum implementation. Even though that study showed that fifth- and seventh-grade students developed their understandings about these topics during the implementation of those curriculum materials, they still struggled with understanding the contributions of both parents to the genetic makeup of their offspring.

In the next section, we will describe research findings on students' ideas about genetics and inheritance for different grade levels, although we will emphasize those ideas that are recurrent for upper elementary students, specifically fifth-grade students. Research shows that students develop some nonnormative ideas about these topics from early ages, and if those ideas are not addressed through instruction they tend to persist in older students (Duncan & Tseng, 2011; Duncan et al., 2009). Similarly, the ways by which students make connections among genetic concepts, such as *inheritance of traits* and *variation of traits*, are not clear. Therefore, what follows is a breakdown of students' normative and nonnormative ideas about genetic inheritance, as well as students' ideas about the interaction between environmental factors and inherited traits.

3.2.1 | Nonnormative ideas about genetic inheritance

Recognizing the equal genetic contributions of both parents first requires recognizing the existence of two parents. This concept is typically recognized by students in relation to humans and other animals. Smith and Williams (2007) reported that seven-year-old students could recognize basic kinship relationships. These authors also reported that a proportion of 10-year-old students could recognize the contributions of both parents to an offspring. These findings were supported by the work of other researchers, as well (Cisterna et al., 2013; Terwogt et al., 2003). However, students often do not view plants as having two parents that reproduce through sexual reproduction. Okeke and Wood-Robinson (1980) found that a large proportion of students involved in their study expressed the belief that sexual reproduction was nonexistent in plants. Similar ideas were suggested by the work of Clough and Wood-Robinson (1985). These ideas were also supported by the work of Lewis and Wood-Robinson (2000), who found that a significant number of students had trouble identifying the meeting of pollen and egg cells as a mechanism for sexual reproduction and thus claimed that plants reproduced asexually.

Students commonly have difficulty understanding that both parents contribute equally to an offspring's genetic makeup (e.g., Clough & Wood-Robinson, 1985; Ibáñez & Martínez-Aznar, 2005; Kargbo et al., 1980). Students tend to demonstrate understanding that genes are inherited from parents and that this is related to offspring's resemblance to parents (Smith & Williams, 2007), but they struggle to explain the mechanisms connecting that resemblance to those inherited genes. This results in a variety of nonnormative ideas about parental contribution.

One common nonnormative idea about parental contribution is that female offspring tend to inherit more genetic information from their mothers, whereas male offspring tend to inherit more genetic information from their fathers (e.g., Ibáñez & Martínez-Aznar, 2005; Kargbo et al., 1980). Another prevalent idea is that mothers contribute more genetic information to their offspring through the process of gestation (e.g., Clough & Wood-Robinson, 1985; Kargbo et al., 1980). The aforementioned ideas illustrate the difficulties students have understanding that parents provide equal genetic contributions to offspring.

Students often find difficulties in making connections in their understandings of parental contributions of genetic information and the expression of traits in offspring (Lewis & Wood-Robinson, 2000; Wood-Robinson, 1994), especially when the traits of parents and offspring differ. One idea held by many students is that a visible difference between a parent and offspring is a sign that genetic information was not passed down by that parent, which means that students believe that a particular trait comes only from one parent. Clough and Wood-Robinson (1985), for example, reported that a number of students involved in their study expressed the belief that if an offspring resembled one parent for a given trait, then that trait must have been inherited directly from that parent, with no genetic input from the other parent.

Yet another challenge that students frequently face as they work to develop an understanding of the relationship between genes and their phenotypical expression is their struggle to recognize these as two interrelated concepts. It has been shown that some students equate genes and traits (Venville & Treagust, 1998; Venville et al., 2005), which means they believe that genes are not distinct from physical traits. For instance, Lewis and Kattmann (2004) reported on the tendency of students participating in their study, aged 14–16 years old, to use terms such as “gene” and “character” interchangeably, demonstrating the absence of a “clear distinction between the genotype and the phenotype” (p. 199). Similar findings were reported by Clough and Wood-Robinson (1985). In their study, they found a number of students who referred to genes as being dominant in a specific organism when that gene is visibly expressed in that organism's phenotype. Research has also shown that students tend to conceptualize genes as passive particles that are passed down from parents to offspring (Clough & Wood-Robinson, 1985; Venville & Treagust, 1998). In this understanding, genes are understood as “trait-bearing” particles (Lewis & Kattmann, 2004; Smith & Williams, 2007), but not as entities that contain information that needs to be translated and expressed as particular traits.

Consequently, when students progress to secondary-level science classes, these confused ideas can make it difficult for them to understand the basic mechanisms for trait expression, particularly because they tend to equate the concepts of genotype and phenotype (Shaw, Van Horne, Zhang, & Boughman, 2008). Moreover, students in these secondary-level classes often locate both concepts at the same level, so they explain that the phenotype “mirrors” the genotype, which implies that students tend to focus their explanations about inheritance on the result of gene expression—the visible trait—instead of the informational component of genes (Lewis & Kattmann, 2004). When used, the concept of allele tends to be represented inaccurately, especially when talking in terms of dominance or recessiveness. Research has demonstrated that students tend to conceive of dominant alleles as stronger, bigger, or more beneficial than recessive alleles (Ayuso & Banet, 2002) or as something that suppresses the trait associated with the recessive allele. Moreover, students may have difficulty understanding simple dominant and recessive patterns of inheritance, including making clear distinctions between genes and alleles (Clough & Wood-Robinson, 1985; Shaw et al., 2008).

Finally, some students struggle to grasp the connections between *inheritance of traits* at the genetic level and *variation of trait* at the phenotypic level. An idea that may be particularly difficult is the role of dominant and recessive alleles in causing variability in the traits of a parent and those of an offspring. For instance, two parents may both have a heterozygous genotype for a particular characteristic, which means that both parents would display the dominant trait. There would be a possibility, though, that their offspring would display the recessive trait. In this case, the offspring would not have inherited the dominant alleles—that is, those associated with the parents' traits at all, an idea that can be troubling for students. Lewis and Kattmann (2004) reported that students tend to conceive of this trait as "hidden" yet still present in the offspring: if a trait "occurred in the family in former generations, … [the trait] must occur again in later generations because these cells are always handed on" (p. 200). Similarly, it has been shown elsewhere that students at both secondary and upper elementary levels have difficulty understanding how homozygous recessive offspring can result from two parents with a heterozygous genotype for a particular trait (Williams et al., 2012).

3.2.2 | Students' ideas about interaction with the environment and inherited traits

Just as students have several nonnormative ideas around the effect of inherited genetic information on an organism's traits, they also struggle to develop an understanding of nongenetic influences on traits and the idea that these environmentally influenced traits are not inherited by offspring. Kargbo et al. (1980) analyzed students' ideas around environmentally produced characteristics and whether these characteristics would be inherited by offspring. When explaining predictions in terms of environmental factors, students cited the sun, water, food, mimicry, or parental care and attention as affecting offspring characteristics (Kargbo et al., 1980). In discussing predictions about environmentally induced characteristics, students were given prompts that involved predicting whether a parent's environmentally induced characteristics would occur in its offspring, whether a parent's environmentally induced characteristics would occur in its offspring with time lapse between the appearance of the characteristic in the parent and the time the offspring is born, and whether environmentally induced characteristics present in both parents would occur in their offspring. They found that some children, even at age 12, believed that environmentally induced traits would be passed on to the next generation, though response patterns varied significantly depending on the organism's characteristic (typically an injury). Examples included students predicting that puppies would be born lame if the mother had had a broken leg or that seedlings would have scars similar to that of the parent. Particularly, 22% of students suggested that if a man's finger were to be lost during an accident, the man's children would inherit fewer fingers than normal. In another example (Wood-Robinson, 1994), young students were questioned about whether the offspring of mice whose tails were surgically removed would be born with or without tails; 19% of the sample maintained that the resulting offspring would have no tails.

Wood-Robinson (1994) also alluded to how a large proportion of students (31%) believed athletic ability was solely inherited, with no impact from the environment. A 16-year-old student said about the offspring of two proficient runners, "yes, I think one of their children will be a good runner, especially the first born" (p. 39). Regarding predictions about environmentally induced characteristics with time lapse, Wood-Robinson (p. 38) discussed students' belief that certain characteristics such as tails of mice and acquired running abilities of athletes may not be present in the subsequent generation, but can be continued over several generations. One student responded, "I think you would probably have ones with … after a time it might end up that babies don't have tails, if he [the scientist] keeps repeating it… it probably would happen, it's hard to say how many generations… well, probably after 4 or 5 generations, they might start to have no tails…"

There was also variability in answers depending on if the organism in question was a human, other animal, or plant. Wood-Robinson (1994) discussed that students between the ages of 12 and 16 attributed variation within a species of plant to environmental causes and not to parentage of the plants. Similar beliefs about animals including humans have been found, but these beliefs are mostly attributed to general familiarity with inheritance patterns based on observations, mass media, or discussions with peers and adults (Wood-Robinson, 1994).

In summary, research literature suggests that at all grade levels, students show widespread confusion in how variation in animals, humans, and plants is associated with parentage and how genes are passed on from one generation to the next. In addition, students face challenges when distinguishing between environmental and genetically inherited traits (Wood-Robinson, 1994). Banet and Ayuso (2000) discussed how students' nonnormative ideas have roots in their difficulty understanding the roles of chromosomes, genes, and alleles in the inheritance of traits. The concept of *variation of traits* and its connection with inheritance of different genetic information for a trait should be taught in earlier grades to develop these basic ideas before the secondary-grade levels. For ideas to be grounded and built around scientific literacy regarding *inheritance of traits* and *variation of traits* without the incorporation of nonnormative ideas, we must provide direction from the early grades, such as from fifth grade, to secondary genetics education around *inheritance of traits* and *variation of traits*.

4 | THEORETICAL FRAMEWORK

Our work draws on the Knowledge Integration framework (Gerard, Spitulnik, & Linn, 2010; Kali, Linn, & Roseman, 2008; Linn & Hsi, 2000; Linn, Eylon, & Davis, 2004). Knowledge Integration informs not only our understanding of how students learn but also our design processes for both the curricular materials and the assessments. The Knowledge Integration perspective emphasizes that well-designed instruction elicits students' repertoire of ideas and encourages them to add new ideas about science phenomena, while also guiding students to sort through their old and new ideas to evaluate them for correctness (Linn, Davis, & Bell, 2004). Underlying this approach are four meta-principles: (a) making science accessible, (b) making thinking visible, (c) learning from others, and (d) promoting lifelong learning. Making science accessible involves asking students to explain personally relevant situations and designing pivotal cases, which are usually cases that compare two different conditions in a controlled experiment and are personally relevant and contain a story (Linn, 2005). These pivotal cases also link existing ideas to normative perspectives (Linn & Hsi, 2000). Making thinking visible involves modeling and evaluating how science ideas are connected (e.g., Casperson & Linn, 2006; Gobert & Buckley, 2000; McNeill, Lizotte, Krajcik, & Marx, 2006; Schwarz & White, 2005; White & Frederiksen, 1998). Learning from others involves placing students in collaborative learning situations (Clark & Linn, 2003). Promoting lifelong learning involves engaging students in reflection on their own scientific ideas through instruction (Davis & Linn, 2000). This study seeks a deeper understanding of how students make sense of new ideas in connection to their existing knowledge and continues research on students' repertoire of ideas related to genetic inheritance.

4.1 | Curricular context: The WISE module

As called for in the Framework for K–12 Science Education (NRC, 2012) and NGSS Lead States (2013), the Grade-5 STEMGenetics curriculum is a 4-week unit that explicitly integrates core ideas, scientific practices, and crosscutting concepts within genetics curricula. Using the Web-based Inquiry Science Environment (WISE), a technology-rich learning environment, along with hands-on activities, the unit engages students in understanding inheritance by answering the driving question *Why do plants of the same species vary in how they look?* Students are introduced to a pivotal case that entails scientists growing and breeding purple- and green-stemmed Wisconsin Fast Plants® (WFP) with the first generation of offspring turning out to be all purple stemmed (a monohybrid cross). Students are then challenged to predict the stem color for the second generation of WFP offspring, which they grow and observe in the classroom. By the end of the unit, students identify patterns of variation that are based on aggregated data from their WFP stem colors that help them to evaluate their initial predictions.

5 | METHODS

5.1 | Participants

This study was implemented in two suburban school districts we partnered with: one in the southern United States and one in the midwestern United States Both districts are socially and economically diverse communities. There are an approximately equal number of male and female students in each district. The percentage of students on free or reduced price lunch is 67% in the southern district and 25% in the midwestern district. Table 1 shows the ethnic/racial demographic information for the two districts.

There were, in total, 486 participants from eight teachers' classes in Grade 5. Five teachers in the southern district taught 259 students, with the remaining three teachers and 227 students located in the midwestern district. The classroom size in both districts varied from 20 to 28. Both districts agreed to use the STEMGenetics curriculum as a means

TABLE 1 Demographics for the two participating districts

Ethnicities	South	Midwest
Caucasian	7%	60%
African American	65%	18%
Asian	1%	9%
Hispanic	23%	7%
Multiracial	3%	5%
Others	1%	1%

Note. Demographics are presented for both the district in the southern state and the midwestern state.

of teaching the core science topic genetic inheritance and of integrating technology into their instructional practices. The curriculum was implemented during the 2012–2013 school year.

6 | ASSESSMENT DESIGN

The assessment team started to develop the assessment in the fall of 2011. The team first reviewed the STEM Genetics 2010 summative assessment in terms of whether items aligned well to the LS3.A and LS3.B core ideas from *A Framework for K–12 Science Education* (NRC, 2012). The team then went over some international, national, and other jurisdictions' science assessments to explore new items. In the spring of 2012, a batch of items was developed to both align with the Framework and match the learning goals of the current curriculum. Based on the feedback from the advisory board, modifications were made to the learning goals of the fifth-grade unit. The items were then put through another review process. This review process involved a content review by the fifth-grade curriculum development teams (scientists, teachers, graduate students, and researchers) and another review of the think-aloud interview of students (six students from each grade in both districts with varying degrees of content knowledge) conducted in the spring of 2012. The following is an example of a fifth-grade assessment item:

6.1 | Original version

> *Jim's grandparents learned to speak both Spanish and English when they immigrated to the United States. Just like his grandparents and his parents, Jim also speaks both Spanish and English. Is the ability to speak both Spanish and English an inherited or acquired trait?* ***Explain your answer***.

6.2 | Modified version

> *David's grandparents spoke Spanish and learned English when they came to the United States. Just like his grandparents and his parents, David also speaks both Spanish and English. Did he inherit the skill to speak both Spanish and English?* ***Please explain your answer.***

First, the item was identified as aligning well with the primary learning goals, which includes the ability of students to distinguish between inherited traits (LS3.A) and those impacted by the environment (LS3.B). Second, the name was changed from Jim to David to make the context more culturally relevant to the population of students participating in the study. Third, the vocabulary "immigrated" was changed to "came to," because some fifth-grade students did not know the word "immigrate."

After months of item modification, the team created an item pool that contained more than 30 items. All items in the item pool were divided into two test forms (Form A and Form B) to be pilot tested in all the sixth-grade classrooms in two school districts (midwestern and southern United States) in the early fall of 2012. Grade-6 students piloted the items because they would have learned this content the prior spring. This method of piloting also provided the opportunity to have students of a wide range of proficiency levels respond to the items. After both districts' test booklets were returned, 100 tests (50 Form A and 50 Form B) at each grade level were randomly selected and coded according to our Knowledge Integration-based rubrics. The interrater reliability was over 0.80.

After the pilot test forms were coded, classical item analyses were conducted. For each item, item difficulty and item discrimination were calculated. Item difficulty is the percentage of students who answer this item correctly; item discrimination is the correlation of the student performance on one item and the total test. Items with low discrimination values were deleted because they cannot effectively differentiate high-achieving students from low-achieving students. The following is an example of a dropped item from the fifth-grade assessment:

Roger had a parrot. He kept clipping its wings so it would not fly away.

(a) Wings of the offspring of this parrot would be _____.

- **A.** missing
- **B.** as long as his parent's before it is clipped
- **C.** shorter than his parent's
- **D.** of same size as the clipped wings

(b) Explain why wing length is inherited or not.

This item aligned well with the learning goal of LS3.A. The problem with this item was that information about the other parent of the offspring parrot is missing. Some students make assumptions about this missing parent. Additionally, there is no information given about the age of the offspring parrot. Examples of student responses for this item that hinged on this missing information include "the wings of the offspring would be shorter because another parent has shorter wings" and "the wings of the offspring would be shorter because the offspring is a baby." Because it would require a large amount of text to provide this missing information to students, the assessment team decided to drop this item.

In addition, distractor analysis was conducted for multiple-choice (MC) items. This analysis calculated the percentage of students selecting each answer choice. Those answer choices that no/few students selected were revised. The following is an example of a revised item from the fifth-grade assessment:

Madison has a pet dog. Which of the following characteristics did the dog most likely inherit from its parents?

- **(A)** ~~The food it likes.~~ A torn ear.
- **(B)** The tricks it does.
- **(C)** The color of its fur.
- **(D)** The place where it lives.

This item aligned well with the learning goal of LS3.A. The distractor analysis revealed that very few students selected the answer choice "A. The food it likes," probably because it is so easy to see that this answer choice is not the correct one. After discussing this item, the assessment team changed it to "A. A torn ear."

After item analysis, an operational item pool was constructed by selecting items with good psychometrical quality from pilot test forms. There were 20 items in the Grade-5 operational pool. Then, the assessment team and curriculum teams worked together to create the final test form. First, each item was aligned to a learning goal by the respective curriculum teams. As the curriculum was being modified during the same period when the assessment was being created, items that did not align well to any learning goals in the updated curriculum were removed. Based on the consideration of testing time, both teams decided that the test length should be approximately 15–17 items with at least one-third MC items and at most two-thirds constructed response (CR) items. The assessment team first constructed the initial version of the final test forms to make sure that the items used covered all the content areas and difficulty levels. These forms were sent to the curriculum teams for further review. After the curriculum teams approved the test

TABLE 2 Test specification for fifth-grade assessment

Learning goals (construct)	MC	MC + CR	CR	Total
Inheritance of traits	5	2	2	9
Variation of traits	1	–	5	6
Life cycle	1	–	1	2
Total	7	2	8	17

Note. MC, multiple-choice item; CR, constructed response item. Total refers to the number of items.

TABLE 3 Item difficulty and discrimination analysis results

Number in final form	Item type	Difficulty revised post	Discrimination revised post
1	MC	0.95	0.25
2	MC	0.88	0.09
3	CR	0.67	0.28
4	CR	0.26	0.39
5	MC+CR	0.40	0.40
6	CR	0.65	0.33
7	CR	0.16	0.47
8	MC	0.69	0.23
9	CR	0.19	0.27
10	CR	0.29	0.28
11	MC	0.49	0.17
12	MC+CR	0.74	0.35
13	CR	0.47	0.38
14	MC	0.70	0.36
15	CR	0.52	0.42
16	MC	0.78	0.32
17	MC	0.82	0.35

forms, the assessment team reordered the items by putting an easy item at the beginning and by balancing item format and content.

7 | ASSESSMENT INSTRUMENT

In the current version of the final test form, there are 17 items. A test was administered as a pre–post assessment to measure and diagnose student learning on heredity prior to and after the 4-week STEMGenetics module. The assessment was a 45-minute test of both MC and CR questions, covering all the key learning goals of the unit. Table 2 lists the key learning goals by item type for the fifth-grade assessment. The items were selected from released state, national and international science assessments such as Michigan Educational Assessment Program, National Assessment of Educational Progress, and Trends in International Mathematics and Science Study, as we found validated questions around the topic of inheritance to be limited and narrowly defined. Items chosen from preexisting assessments were modified as needed to align with the LS3.A and LS3.B core ideas (NRC, 2012). (See the Appendix for the complete Grade-5 assessment.)

Tables 3 lists the difficulty and discrimination values of the 17 items in the final test and shows that 17 items have a range of difficulty levels from 0.16 to 0.95. This is a good coverage of both easy and difficult items in the test. They all have positive item discrimination values, which are desirable, meaning students with higher achievement overall on the subject tend to answer correctly on these items. Only a couple (Q2 and Q11) are below reasonable acceptance rate, which is usually between 0.2 and 0.3 in practice. However, due to the already small number of items for this test, we decided to leave them in instead of eliminating more items.

An adapted Knowledge Integration rubric from Linn, Lee, Tinker, Husic, and Chiu (2006) was constructed and applied to score pre- and posttest assessment items and to examine how students linked relevant normative ideas about genetics and used them to construct explanations. While understanding students' relevant but nonnormative ideas can be a useful contribution to research and practice, it was not the focus of this study. The focus was on understanding students' normative ideas. We realize that this is a limitation of our study. The Knowledge Integration rubric allowed for an analysis of how students integrated their ideas when answering the assessment item. To describe patterns of *inheritance of traits* and *variation of traits* in offspring, we focused on the second Knowledge Integration metaprinciple of making thinking visible, which was especially relevant to the rubric design. Even when students expressed nonnormative or irrelevant ideas in their short answer responses or via their selection of incorrect MC options, our rubric still captured students' attempts to provide a foundation for these ideas in their normative understandings of the inheritance of traits (e.g., that traits are inherited from parents or run in families).

By drawing from the Knowledge Integration lens, we categorized the ideas, or beliefs about the concepts of *inheritance of traits* and *variation of traits*, that students articulated and the conceptual connections they made in the open-ended response questions as constituting either an irrelevant, isolated, partial, or complete explanation, which delineated the levels of conceptual sophistication in the students' scientific explanations (Liu, Lee, & Linn, 2011). If students had only irrelevant nonnormative and/or normative ideas in a given context, then their explanation would fall under an irrelevant explanation and would be scored as 0. If students had a relevant normative idea but failed to recognize links with other relevant normative ideas, then their explanation would fall under an isolated explanation and would be scored as a 1. If students had more than one relevant normative idea but did not fully elaborate links between these normative ideas in a given context, then their explanation would fall under a partial explanation and would be scored as a 2. Lastly, if students elaborated a scientifically valid link between two or more relevant normative ideas relevant to a given context, then their explanation would fall under a complete explanation and would be scored a 3. For fifth-grade students, it was not expected that they would be able to form a complete explanation for genetics-based phenomena related to *inheritance of traits*, since many of the underlying ideas are only appropriate for more advanced students. Thus, the rubrics for some CR assessment items stopped at a Level 2.

Raters with expertise in science content and teaching were randomly assigned to teacher classes and student responses and trained to use the scoring guide to score randomly deidentified student responses. The raters agreed on the scores for the students. Disagreements were resolved by discussions. The interrater reliability ranges from 0.6 to 0.96 ($N = 10$ raters) for CR items in the pre- and posttest.

In the process of scoring, researchers experienced difficulties applying the rubrics to some of the students' responses and extensive discussions ensued around a couple of items of interest. An iterative process of revision of the rubric, based on several rounds of team feedback and review of samples of student work, was needed for refinement. As a consequence, two of the CR questions, 9 and 10, were rescored based on the new rubrics. The existing scores for the other CR questions based on the unrevised rubrics were maintained. Table 4 lists the description of the different levels of Knowledge Integration and their corresponding levels of understanding for the CR questions.

7.1 | Model

To further examine the relationship between students' understanding of major concepts of genetics, we applied structural equation modeling (SEM), a theory-driven data analysis process widely used by educational scientists (Mueller & Hancock, 2010; Raykov, 2006). SEM includes latent variables that are estimated from measured variables and captures measurement error in the model. In particular, we performed confirmatory factor analysis (CFA), a special case of SEM, to investigate the relationship between the two latent variables, *inheritance of traits* and *variation of traits*. Since CFA handles measurement error from observed items better than correlation and regression analysis, it would be

TABLE 4 Scores for CR questions

Description of level of Knowledge Integration understanding	Level of Knowledge Integration
Irrelevant understanding: Students have irrelevant nonnormative and/or normative ideas in a given context.	0
Isolated understanding: Have relevant normative ideas but fail to recognize links between them.	1
Make links between relevant and irrelevant normative ideas.	
Partial understanding: Have relevant normative ideas but do not fully elaborate links between them in a given context.	2
Complete understanding: Students understand how two scientific concepts interact in a given context. Elaborate a scientifically valid link between two relevant normative ideas to a given context.	3

anticipated that the relationship between *inheritance of traits* and *variation of traits* can be more accurately delineated using CFA. For this CFA, only posttest data were used as our aim was to understand students' knowledge on genetics after the implementation of the STEMGenetics curriculum. In other words, we looked at internal construct validity between the assessment items and the core ideas of *inheritance of traits* and *variation of traits*.

8 | FINDINGS

In this section, we first state the major findings. Next, we unpack each finding and relate it back to the research questions. The first major finding addresses our first research question of, "How do upper-elementary students make connections between ideas related to *inheritance of traits* and those of *variation of traits*?" CFA, supplemented with qualitative analyses of students' responses on the posttest, revealed a relationship between the concepts of *inheritance of traits* and *variation of traits* and contributed evidence about the nature of students' difficulties in understanding these two concepts as interrelated.

Our second finding addresses the research question: "What is their ability to integrate knowledge and make scientific connections around these core ideas?" While most students showed some normative ideas and identified generational patterns of visible traits (e.g., traits skipping a generation), many struggled to explain *variation of traits* as resulting from the inheritance of different information from each of two parents. They recognized that information was inherited but did not elaborate by saying that the variation of traits was caused by different inherited information from both parents.

8.1 | Overall student performance and learning gains

After weeks of hands-on activities growing WFP in the classrooms, as well as interacting with simulations within the online Web-based Integrated Science Environment (WISE), most students demonstrated understanding that genetic information is passed from parents to offspring and that variation results from genetic inheritance and environmental influences. These understandings were evaluated using a posttest identical to the pretest they completed before the unit.

The pre- and posttest are both reliable measures of student performance with Cronbach α of .61 and .66 for both assessments, respectively. The Cronbach α values are for the whole test, not on subscale, indicating that the tests developed are a reliable measurement. The data analyses were focused on two main constructs: *inheritance of traits* and *variation of traits*. The sample selected for data analysis includes all the fifth graders who took both pre- and posttest in the school districts. Students who missed either pre- or posttest were treated as missing at random and deleted pairwise. Thus, the sample size is 474, dropped from a total of 486 participants.

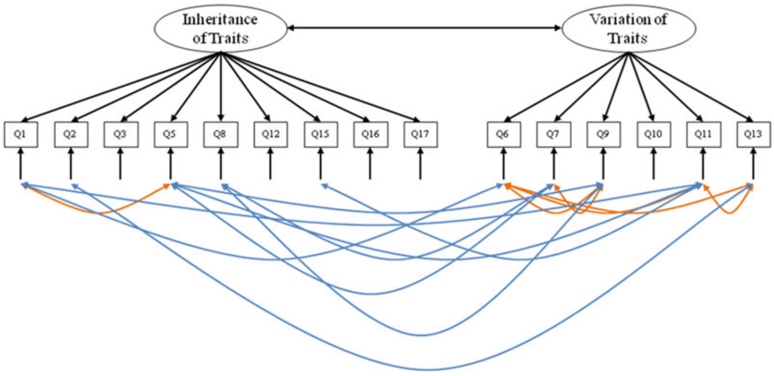

FIGURE 1 Path diagram of the confirmatory factor analysis model with *inheritance of traits* and *variation of traits* [Color figure can be viewed at wileyonlinelibrary.com]

8.2 | Relating students' understanding of inheritance of traits and variation of traits concepts using SEM modeling

Correlated error covariances between some specific item pairs are included based on a theoretical rationale established by the research team of content experts. The research team of content experts spent several rounds unpacking these items and linking some but not all items based on the content and concepts to yield. Fifteen items, nine items for *inheritance of traits* and six for *variation of traits*, were included in the model. Items 10, 12, 16, and 17 were not linked in this specific model. Items 4 and 14 were not included as they were linked to the life cycle concept. With our limited and correlated assessment questions, we came up with a satisfying CFA model that we see merit of discussing. The path diagram for the CFA model is displayed in Figure 1.

The two-way arrow between the two latent variables, the two constructs of interest of *inheritance of traits* and *variation of traits*, represents the factor correlation. The one-way arrows connecting the construct of either *inheritance of traits* or *variation of traits* to the test items are the factor loadings, indicating the correlation between them. The one-way arrows pointing to the test items are the error terms, the unexplained variance by the common construct. This unexplained variance includes the variance of a specific item and random measurement error. The two-way arrows linking the errors are the proposed error covariances. The error covariances included in this model are for six within-construct question pairs (Q1, Q5), (Q6, Q9), (Q6, Q11), (Q6, Q13), (Q7, Q9), (Q11, Q13), and nine between-construct question pairs (Q1, Q6), (Q1, Q11), (Q2, Q13), (Q5, Q7), (Q5, Q9), (Q5, Q11), (Q7, Q8), (Q8, Q9), (Q11, Q15). Error terms can be correlated because theoretical evidence supports the idea that understanding the common factors behind these items will help to explain students' understanding of the two major concepts.

The proposed model was estimated using the Mplus version 6 (Muthen & Muthen, 2010). The combination of model fit indices (Hu & Bentler, 1999) suggests that the proposed factor structure fit the data reasonably well. The chi-square value $\chi 2\ (74) = 93.932$, $p = .06$ indicates that there is strong evidence not to reject the model at the level .05. Also, the comparative fit index is 0.972 and the Tucker–Lewis index is 0.96, both greater than the threshold level 0.95. The root mean square error of approximation is 0.024, smaller than the cutoff value 0.06; and the 90% confidence interval is (0.000, 0.037). Therefore, the proposed model described the data very well.

The factor loadings on the constructs are listed in Tables 5 and 6. The factor loadings show the correlation between each observed measure, the test item in this case, and an unobserved construct, either the construct *inheritance of traits* or *variation of traits*. Their square value shows the variance explained by the corresponding construct. Considering loadings above 0.6 to be high and below 0.4 to be low (Hair, Anderson, Tatham, & Black, 1998), the factor loadings in this study provide evidence that the items are valid in measuring the target constructs of *inheritance of traits and variation of traits* specified in this study. As shown in Tables 5 and 6, the *t*-values (i.e., estimate divided by standard error [*SE*]) demonstrate that all factor loadings are significant. The factor correlation coefficient between *inheritance of traits* and

TABLE 5 Factor loadings on the subscale inheritance of traits

Item (inheritance)	Factor loadings estimate	Standard error	*t* value
Q1	0.750	0.068	11.027
Q2	0.502	0.074	6.822
Q3	0.505	0.054	9.426
Q5	0.506	0.072	7.062
Q8	0.348	0.056	6.198
Q12	0.409	0.056	7.251
Q15	0.393	0.061	6.478
Q16	0.222	0.098	2.261
Q17	0.584	0.131	4.467

TABLE 6 Factor loadings on the subscale variation of traits

Item (variation)	Factor loadings estimate	Standard error	*t* value
Q6	0.584	0.073	7.970
Q7	0.347	0.068	5.120
Q9	0.599	0.071	8.479
Q10	0.593	0.064	9.263
Q11	0.338	0.082	4.134
Q13	0.417	0.060	6.977

variation of traits is .97 ($p < .001$). Although the fact that these two constructs are highly correlated suggests a common underlying construct, they are well defined as distinct constructs from a biological perspective, as represented in Figure 1. Thus, they are treated as separate constructs to further explore students' understanding of these two concepts. Table 7 shows the correlated error covariances between items and separated by within constructs and between constructs.

We looked at the overall significant correlated error covariances. Correlated error terms suggest a situation in which the two items are measuring a concept that is not completely identical to either of the common constructs. Students' understanding of this concept affects their performance on both questions. As seen in Table 7, there are 10 question pairs between the constructs of *inheritance of traits* and *variation of traits*. The range of the error covariance is between –0.385 and 0.280. Overall, the negative correlation was between a MC question and a CR response question, where the likelihood of students scoring well on the MC question was higher than that of the CR question. The interesting finding, though, lies in interpreting the four pairs with positive covariances. The question pairs that generated a positive correlation between the constructs of *inheritance of traits* and *variation of traits* were question pairs Q8 and Q9, Q5 and Q9, Q5and Q11, and Q11 and Q15. The two question pairs that are significantly positively correlated are question pairs Q8, Q9, and Q11, Q15. For example, the estimated error covariance between Q8 and Q9 is 0.28 with a *SE* of 0.06. Even though the correlation is not high, the *t*-value is significant ($p < .001$), and the positive correlation of .28 means that if a student were to have trouble responding to Q8 correctly, then that student would be unlikely to get a high score on Q9. In other words, for both Q8, which is a MC item, and Q9, which is a CR item, students need to be able to explain that traits come from both parents and that the offspring gets different information from the parents, which is why the offspring will not be identical to the parent. Q8 deals with multiple offspring and how both parents contribute to the genetic makeup of the various offspring and Q9 requires an understanding of differences in inherited information resulting in variation in traits. (See Figures 2 and 3 for Questions 8 and 9, respectively.)

TABLE 7 Error covariances between items

Error correlation included in model	Correlation estimate	Standard error (*SE*)	Estimate/*SE*
Q1 with Q5	−0.342	0.141	−2.430
Within construct: Variation			
Q6 with Q9	−0.146	0.093	−1.580
Q6 with Q13	0.014	0.110	0.129
Q7 with Q9	−0.182	0.086	−2.101
Q11 with Q13	0.169	0.095	1.774
Between constructs: Inheritance and variation			
Q5 with Q7	−0.216	0.096	−2.261
Q7 with Q8	−0.118	0.091	−1.302
Q8 with Q9	0.280	0.061	4.615
Q2 with Q13	−0.352	0.080	−4.415
Q1 with Q6	−0.202	0.148	−1.366
Q5 with Q9	0.130	0.072	1.800
Q5 with Q11	0.114	0.074	1.540
Q6 with Q11	−0.151	0.135	−1.120
Q11 with Q15	0.194	0.075	2.579
Q1 with Q11	−0.385	0.158	−2.429

(Q8) Susan has a miniature (short) female poodle and standard (tall) male poodle. These two poodles had two standard poodle puppies and two miniature poodle puppies.

Circle the statement that is TRUE.

A. The standard poodle puppies inherited height from the dad.

B. The miniature poodle puppies inherited height from the mom.

C. All four poodle puppies inherited height from both parents.

D. Height is not an inherited characteristic.

FIGURE 2 Question 8 [Color figure can be viewed at wileyonlinelibrary.com]

Another example pair is Q11 and Q15. Their estimated error covariance is 0.19 with a *SE* of 0.07, and the *t*-value is 2.58 ($p < .001$). Question 11, which is a MC question, requires an understanding of variation of inherited information among various cat offspring. To respond to Q11, students have to know that the information for those traits is coming from both parents. Q15, then, which is a CR item, requires that students understand that traits that are environmentally influenced in a parent, such as having a dog's tail bobbed or cut off, are not passed down to their offspring. Q15 builds on the knowledge tested in Q11 that information for a trait is passed down from both parents, in this case dogs, (Q9) Maria and John both have dimples. They have a daughter named Katie. Katie has no dimples. How is it possible for two parents with dimples to have a child with no dimples?

FIGURE 3 Question 9

11. George is a white cat and Hilda is a black cat. George and Hilda have four kittens: one black, one white, and two gray. Information for color is inherited.

Circle the statements that are TRUE.

A. The gray kittens inherited their color from both parents.

B. The black kitten inherited its color only from the mom.

C. The white kitten inherited its color only from the dad.

D. All four kittens inherited the color from both parents.

FIGURE 4 Question 11

15. Some show dogs have their tails “bobbed” or cut off when they are young. When they grow up and have puppies, will the puppies be missing their tails as well?

Please explain your answer.

FIGURE 5 Question 15

but students must also distinguish between environmental influences and inherited traits in these two questions. Both pairs of examples presented here are between-construct pairs. Though each item individually is measuring one particular construct, the correlation between the items shows some underlying common concept for the two items across both constructs. Therefore, using SEM modeling analysis showed that there was an underlying concept between these two constructs and that if students did not understand an item on the construct of *inheritance of traits*, then the likelihood of getting a high score on an item on the construct of *variation of traits* would be low. (See Figures 4 and 5 for Questions 11 and 15, respectively.)

8.3 | Unpacking students’ understanding: Illustrating Knowledge Integration

To elaborate the findings from the CFA model, we discuss specific ideas and connections related to *inheritance of traits* and *variation of traits* that were particularly challenging for fifth graders as indicated by posttest responses. What follows addresses our second research question, “What is their ability to integrate knowledge and make scientific connections around these core ideas?” Table 8 provides a breakdown of the 474 students’ overall score in each of the nine CR and MC + CR items across the four levels of Knowledge Integration. In general, students fell under a Knowledge Integration level of 1 for questions within constructs (Q5, Q13, and Q15) and in between constructs for these items (Q9 and Q10).

TABLE 8 Frequency of student scores for CR and MC + CR items

Item number	Item type	Students scoring left item blank	Student scoring at Knowledge Integration level 0	Students scoring at Knowledge Integration level 1	Students scoring at Knowledge Integration level 2	Student scoring at Knowledge Integration level 3	Standard code and description
Q3	CR	4	82	125	263	0	LS3.A Inheritance of Traits
Q5	MC + CR	3	26	303	136	6	LS3.A Inheritance of Traits
Q6	CR	9	62	147	256	0	LS3.A Inheritance of Traits
Q7	CR	19	233	159	63	0	LS3.A Inheritance of Traits & LS3.B Variation of Traits
Q 9	CR	17	196	240	20	1	LS3.A Inheritance of Traits & LS3.B Variation of Traits
Q10	CR	19	150	201	102	2	LS3.A Inheritance of Traits & LS3.B Variation of Traits
Q12	MC + CR	15	38	119	302	0	LS3.A Inheritance of Traits
Q13	CR	26	54	350	44	0	LS3.B Variation of Traits
Q15	CR	29	81	216	148	0	LS3.A Inheritance of Traits

As seen in Table 8, for Q3, Q6, and Q12 where the wording was less complex, the majority of students demonstrated a Knowledge Integration Level of 2. In other words, students had relevant normative ideas within the construct of either *inheritance of traits* or *variation of traits* but did not fully elaborate connections between them. In Question 3, students were expected to distinguish environmental influences such as the learned behavior of learning a language and inherited characteristics. Q6 gets at how environmental influences can impact an organism's trait such as plant height, in addition to being able to expound upon what specific factors can contribute to the observed differences. Lastly, in Q12, students are asked to address whether the offspring flower looks like the parent flower and recognize that traits are passed down from parents to offspring. (See Appendix for the complete assessment and Q3, Q6, and Q12.

We now provide examples of how responses exhibited problem concepts students had in making scientific links between these two constructs by using Question 9 as an example. Figure 6 shows the scoring rubric used for the CR Question 9. The scoring rubric has four levels of Knowledge Integration along with a description, examples of student responses for each level, and clarification of student responses and why they are at that level. In our scoring of students' explanations, we looked at the number of normative and relevant ideas students had about *inheritance of traits* and/or *variation of traits* and the scientific links they made between these normative and relevant ideas to justify their explanation (Liu et al., 2011). As part of our analysis process, we created four different categories of student explainers based on the level of Knowledge Integration understanding (see Table 4) they fell under. These levels of student explainers were complete ideas explainers, partial ideas explainers, isolated ideas explainers, and irrelevant ideas explainers. Figure 6 provides examples of these different levels of student explainers.

For fifth grade, the expectation was that students' performance on Question 9 reflected an understanding that you inherit different information for traits from both your parents (NGSS Lead States, 2013; NRC, 2012). For this question, the students did not see the grandparents for the dimple trait, with each grandparent carrying either two recessive ("no dimples") alleles for the dimples trait or two dominant alleles ("dimples") for the dimples trait. Instead, the question

(Q9) Maria and John both have dimples. They have a daughter named Katie. Katie has no dimples. How is it possible for two parents with dimples to have a child with no dimples?

Rubric for Question 9

Score	Knowledge Integration Explanation	Description	Example of student work	Student Response Clarification
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK	
0	**Irrelevant Knowledge Integration** Students have irrelevant normative or/and non-normative ideas about inheritance of traits or variation of traits.	Katie is adopted. OR 50/50 chance Katie would have dimples Katie didn't get that trait from her parents. OR Off task – write something that is not relevant to the item OR student repeats the question	Student G: Maria and John might have dimples but that doesn't mean Katie will have dimples because It's not going to show the dimples on Katie.	Student G is not adding any new relevant normative ideas and is repeating what is in the question. They do not add any normative ideas about inheritance of traits or variation of traits.
			Student H: because Katie's parents ar old lik 50 years old, but Katie is probibly gust 3 years old. Student I: When they were little they had dimples but they got older and they didn't have any more dimples.	Students H and I expressed the irrelevant non-normative idea that dimples are a product of age.
1	**Isolated Knowledge Integration** Have relevant normative ideas about either variation of traits or inheritance of traits but fail to	Katie inherited the no dimples trait from her parents. OR The no dimples trait skipped a generation OR She got the no dimples trait from her grandparents (or other relative)	Student D: It's possible because you don't have to inherit all the traits that both of your parents have.	Student D expressed the relevant normative idea that traits are inherited from parents.
	Make links between relevant normative ideas and irrelevant normative ideas.		Student E: A grandparent or aunt uncle or anybody else in the family	Student E expressed the relevant normative idea that the no-dimples trait came from a grandparent.
			Student F: the grandparent's could not have dimples so the child has no dimples.	Student F expressed the relevant, normative idea that expressed traits aren't necessarily visible in every generation, but links it to the non-normative idea that offspring can inherit traits directly from the grandparents, with no input from the parents.
2	**Partial Knowledge Integration** Have relevant normative ideas but do not fully elaborate links between them in a given context.	Students specify not having dimples is a recessive OR having dimples is dominant with no specific mention of what Katie inherited from her parents. OR Katie received the no dimples allele/gene from both parents (with no mention of dominant/recessive alleles).	Student B: Maria's or John's parents may have had no dimples and passed the gene on to Maria or John, but that gene was not dominante. In Katie, that gene was dominante.	Student B expressed the relevant normative ideas within the construct of inheritance of traits that the grandparents had the no-dimples trait and that the no-dimples gene was passed on to either Maria or John.
	Normative ideas within construct (either inheritance of traits or variation of traits)		Student C: The parents had no-dimple genes in them that stayed inactive until they were passed on to.	Student C expressed relevant normative ideas that Katie's parents had no-dimple genes that were "inactive" or did not get expressed and were passed on to Katie.
3	**Complete Knowledge Integration** Students understand how two scientific concepts interact in a given context. Elaborate a scientifically valid link between two ideas relevant to a given context.	Not having dimples is a recessive trait. Both Katie's parents are carriers (heterozygous) of the no dimples allele and both gave her the recessive allele.	Student A: It's possible, because in Katie's genes she got a *rr* for dimples. So that *rr* means she won't have dimples. That's a possible reason why Katie has no dimples.	Student A expressed the normative relevant ideas that Katie inherited *rr* for dimples and was able link it to the no-dimples traits not being expressed in Katie.

Note. Student Answers are transcribed exactly as written by students. The student examples are from the post-test student responses showing the categories of student explanations and examples of complete ideas Explainers, partial ideas explainers, isolated ideas explainers, and irrelevant ideas Explainers.

FIGURE 6 Question 9: Scoring rubric and student examples started with the parents, Maria and John. The question asked the students how Maria and John could have a daughter, Katie, without the dimple trait. In this case, students had to know that variability occurs because the offspring are getting different inherited information from both parents. Therefore, Katie inherited information for the no-dimple trait from her parents. Figure 6 shows the scoring of Question 9 as well as examples of student responses representing the different levels of understanding, with fifth graders expected to reach level Knowledge Integration score of a level 2 only. In this way, the scoring guide reflected the continuum of the understanding on this concept (Duncan et al., 2009; NGSS Lead States, 2013; NRC, 2012). However, we did allow fifth graders to reach beyond a Knowledge Integration score of a 2 if they could.

*Complete ideas explainer*s are those more likely to recognize that the parents have variable genetic information, and hence that Katie had a different phenotype compared to her parents. They scored a Knowledge Integration score of a 3 because they were able to make complete links between the normative ideas of *inheritance of traits* and *variation of traits*. For Question 9, only Student A scored a 3. Although Student A's response (It's possible, because in Katie's genes she got a *rr* for dimples. So that *rr* means she will not have dimples. That's a possible reason why Katie has no dimples) is not a representative example of the depth of understanding expected from the Grade-5 students after the STEMGenetics unit, it demonstrates that the student has the potential for elaborating scientific links between the normative ideas relevant to *inheritance of traits* and *variation of traits.* The student mentioned the possibility that Katie, the daughter, could have inherited the recessive trait for dimples (*rr*). Student A was able to make the direct linkage of *variation of traits* and traits in offspring to passage of variable genetic information.

Partial ideas explainers fell under a Knowledge Integration score level of a 2 as they had normative ideas in their responses, but within a construct. Most of their normative ideas were under the construct of *inheritance of traits*. For Question 9, only 20 students were *partial ideas explainers*. These *partial ideas explainers*, as evidenced by the examples given, were recognizing contributions from both parents, as well as passage of genetic information. They used terms such as “dominante” and “inactive” to describe genetic expression. They also used the words “passed on” to indicate that the dimple trait was inherited across generations.

Isolated ideas explainers, who scored a Knowledge Integration score of 1, tended to recognize that the dimple trait is an inherited trait. For Question 9, most students , 240 out of 474, fell under a level 1 and were *isolated ideas explainers*. These *isolated ideas explainers* tended to elicit only one of the normative ideas about either *inheritance of traits* or *variation of traits*. These students did not generally link the trait to the inheritance of genetic information for the dimple trait from both parents and had difficulty understanding the concept of generations. Most students in this Knowledge Integration category of 1 provided explanations that focused on finding generational patterns and recognizing that not all traits are inherited from parents. Many of the students talked about the dimples trait as having “skipped a generation” or as having been “inherited from the grandparent.” They seemed to have an understanding of generations in terms of family trees, focusing on coming up with patterns they can see in their own family trees. In general, student responses at this Knowledge Integration level of 1 stated that offspring inherit traits from grandparents, aunts, uncles, cousins and siblings because family members point out the resemblance between students and their relatives. Most students, after the STEMGenetics unit, fell under *isolated ideas explainers* for the CR and MC + CR items (see Table 8).

Lastly, *irrelevant ideas explainers*, who scored a Knowledge Integration score of 0, made no linkage between *inheritance of traits* and *variation of traits.* For Question 9, there were 196 students who scored a level 0 and fell under irrelevant ideas explainers. Students at this level tended to state that not all traits are inherited. In other words, students understand that there is variation in the way offspring look in comparison to their parents (e.g., Student G). Yet, as shown in the responses of Students G, H, and I, they held nonnormative ideas about the influence of environmental factors on inherited traits, such as that age could influence whether Katie had the dimple trait. For students at this Knowledge Integration level, an offspring does not resemble its parents because as the offspring grows older, the physical trait of dimples disappears with age. At this Knowledge Integration level, they attribute the trait to environmental factors such as aging. Irrelevant ideas explainers who scored a Knowledge Integration score of 0 made no linkage between *inheritance of traits* and *variation of traits*.

In sum, students at the *complete* and *partial linkage* Knowledge Integration levels showed some degree of understanding of the *variation of traits* that exists across generations. Students that were *isolated ideas explainers* and *irrelevant ideas explainers* recognized that offspring vary from their parents. Yet many students, particularly the *isolated ideas explainers* and *irrelevant ideas explainers*, had difficulty conceptualizing this variation as an outcome of both parents' different genetic contributions. Many *isolated ideas explainers* focused on visible patterns of traits across generations, thinking that all traits are immediately apparent or by default "skip a generation." *Irrelevant ideas explainers*, meanwhile, were more likely to rely on a number of nonnormative factors to explain the variation between parents and offspring, prominently time and age. For many students, the idea still persists that the *inheritance of traits* can be attributed to parents, without necessarily linking this inheritance to the passage of variable genetic information from both parents. In general, students experienced difficulties in making direct links between the two constructs of *inheritance of traits* and *variation of traits*.

9 | DISCUSSION

The purpose of this study was to explore younger students' understanding of *inheritance of traits* and *variation of traits*, as well as to examine what kind of scientific connections they made between these concepts after they engaged in the STEMGenetics unit.

The specific research questions investigated were the following:

- How do upper elementary students make connections between ideas related to *inheritance of traits* and those of *variation of traits*?
- What is their ability to integrate knowledge and make scientific connections around these core ideas?

The results (see Figure 6) showed that students in general understood that *variation of traits* occurs among offspring and that traits are inherited from an offspring's parents. The Knowledge Integration framework allowed us to see the learning that took place, as well as what ideas students chose to explain in connecting the two core concepts of *inheritance of traits* and *variation of traits*. The SEM analysis revealed several pairs of items across the constructs *inheritance of traits* and *variation of traits* for which students' performance was correlated, indicating that these cross-construct items were assessing some common concept. These results validated the relationship between the two constructs of *inheritance of traits* and *variation of traits* and revealed a relationship between these two core ideas. They also indicated that students experienced difficulties in connecting these core ideas as evidenced in CR Questions 7, 9, and 10 (see Table 8).

In addressing our second research question of," What is their ability to integrate knowledge and make scientific connections around these core ideas?," our findings show that the majority of students are able to integrate knowledge around the core ideas of either *inheritance of traits* and *variation of traits* but not both as they mostly fell under a Knowledge Integration level of 1 (see Table 8). Our findings also illustrate that students can reason about some abstract ideas at this age level. In their posttest responses, students' reasoning about *inheritance of traits* was no longer about one parent providing most (or all) of the genetic information and traits (Clough & Wood Robinson, 1985). In addition, our results show that students were able to ascribe *variation of traits* to plants, a concept that researchers such as (Duncan et al., 2009) pushed for in their learning progression of genetic concepts that upper elementary students should know as shown in Table 8 in CR item 7. However, some problematic ideas that surfaced in the posttest student responses were around the terms *trait* and *generation*. A possible explanation for these problematic ideas may be that students did not differentiate between traits and characteristics. As Lewis and Wood-Robinson (2000) have found, students may be able to use inheritance terms such as generation and trait but not necessarily understand the underlying concepts behind them. The word *generation* is not explicitly stated in the NGSS Lead States (2013) for the grade band 3–5. The word *characteristic* is mentioned in LS3.A: Inheritance of Traits, as the following "Many characteristics of organisms are inherited from their parents." (NRC, 2012). It is also mentioned under the Clarification Statement of the Performance Expectation for Grade 3 under 3-LS3-1 stating that the emphasis should be on students understanding that, "[p]atterns are the similarities and differences in traits shared between offspring and their parents, or among siblings. Emphasis is on organisms other than humans." However, some of the student responses indicate a

TABLE 9 Overview of problem concepts around inheritance of traits and variation of traits

Problem concepts	Description of problem concepts
Absence of traits and generational patterns	Students explaining absence of traits in terms of generational patterns, such as family trees. This in turn led to overall responses of traits as “skipping a generation” and therefore traits either “later showing up,” “hidden,”, or “inactive.”
Characteristic versus trait	Students not understanding that a trait is a genetically distinguishing characteristic.
Trait as inherited	Students explaining a trait as inherited and not understanding that information for a trait is what is inherited. Students also explained traits as not being always inherited
Traits and environmental factors	Students explaining *inheritance of traits* and *variation of traits* in terms of environmental factors such as age. For example, you get a dimple trait when you grow older.

misunderstanding of what is exactly inherited in a characteristic or understanding that a trait is a genetically distinguishing characteristic. For example, Student D in Q9, who scored a Knowledge Integration score of 1, showed a misunderstanding in their answer of what is inherited: “It's possible because you don't have to inherit all the traits that both of your parents have.” Student D's answer indicates a belief that traits are inherited. However, organisms inherit information for their traits, rather than inheriting each trait directly and wholly from a single parent. This misconception seemed to be the foundation for a lot of the nonnormative ideas expressed at this level. Our findings indicate that upper elementary students struggle in explaining that the underlying scientific phenomena behind *inheritance of traits* is that different information is inherited from each parent which in turn explains why traits are different in organisms. In other words, students explaining trait as inherited suggests that students are not understanding that “different organisms vary in how they look and function because they have different inherited information” (NGSS, 2013, 3-LS3-1, p. 20). Students struggle with the abstract concept of information as it relates to inheritance of traits.

Moreover, our study shows that many of the *isolated ideas explainers*, who scored a 1 and did not integrate ideas between the core ideas of *inheritance of traits* and *variation of traits*, were unable to identify that some traits can go unexpressed in one particular generation, although the genetic information is still present within members of the generation and can be inherited by their offspring. In their posttests, some of these students would explain the absence of a trait in one generation as a result of a generational pattern such as “skipping a generation.” Along the same lines as the normative ideas of “skipping a generation” and finding generational patterns, some students would explain that the trait was “hidden” for a specific generation but that it would “show up” in another generation. This is an idea that Lewis and Kattmann (2004) had also found in their study with students between the ages of 14–16 years old. In our study, we believe that these word choices (e.g., the trait being “hidden” or “later showing up”) may indicate that the teachers may have used these words during their instruction while facilitating classroom discussion around *inheritance of traits* and *variation of traits* as they were terms that showed up in the student responses who fell under *isolated ideas explainers*. Another probable explanation for students using these word choices in their posttests is that the teachers may not have prompted their students to further articulate their thinking and elaborate what they meant when describing the trait as “hidden” or “later showing up.” Another term that came up that was problematic was “inactive” to describe a trait that is not expressed in one generation but expressed in another one. In their study, Ergazaki, Valanidou, Kasimati, and Kalantzi (2015) found that 60 preschoolers aged 5–5.5 years were able to reason about inheritance when supported by a teaching intervention. Using a teaching intervention, such as probing, could further help make more explicit students' thinking and reasoning about what terms such as “hidden” and “later showing up” and help with understanding abstract phenomena. Table 9 highlights the problem concepts students had around the core ideas of *inheritance of traits* and *variation of traits*.

Possible refinements of genetics curriculum in the upper elementary regarding phenomena about *inheritance of traits* and *variation of traits* may be needed. This study builds on Shea's (2015) argument to take into account the level of sophistication needed to understand constructs such as *inheritance of traits* and *variation of traits* at the upper elementary level. It also takes into account what Tsui and Treagust (2010) suggested in their study about students struggling with learning genetics because of the need for students to develop "multilevel thinking." In other words, they emphasized the need to consider further unpacking other concepts, such as generations, students are likely to encounter while learning about *inheritance of traits* and *variation of traits*. Otherwise, students are likely to use relevant terminology, such as "generations" or "skipping a generation" without necessarily having a more advanced understanding of its relationship to *inheritance of traits* and *variation of traits*. As Ross, Lee, Radebuagh, and Stargell (2012) also suggested, students' "perceived understanding" of terminology is equally as important as their true level of understanding. In this case, we suggest specific content knowledge around these terms added in the curriculum. Although, the term generation is not found explicitly in the NGSS Lead States (2013), we suggest that it may need to be added as part of the big ideas that students will encounter in the grade band of 3–5. As mentioned before, the core idea of *variation of traits* is found under LS3.B and states that students should understand that "different organisms vary in how they look and function because they have different inherited information" (p. 20). We recommend adding after different inherited information: "across generations." By bringing in the term "generations," students will also be able to connect how variability of inherited information is related to inheritance patterns across generations in the same family. Teachers could have further engaged in the instructional routine of explicitly speaking (Avenia-Tapper, Haas, & Hollimon, 2016) to scaffold the appropriation of terms such as generation and trait.

10 | IMPLICATIONS

We highlight here the implications for curriculum design. Moreover, we also tie these implications to the importance of student learning.

10.1 | Implications about curriculum design and student learning

Implications for designing curriculum that elicits students' ideas about different inherited information in the context of humans and other animals, not just plants, are suggested. As our findings indicate, students experience difficulty conceptualizing what about the inherited information made one generation different from another one. Although the expectation at this grade level (NGSS Lead States, 2013; NRC, 2012) is not for students to develop and articulate an understanding of alleles and the related patterns of inheritance to these alleles, it is still important to incorporate activities that help students conceptualize what the word "different" might mean in terms of inherited information.

At this age level, helping students conceptualize and visualize how inherited information from each parent can be different will push the students further along in understanding the variability of inherited information and its relationship to *inheritance of traits*. We suggest including activities in the curriculum about family trees and using different colored marbles, for example, to indicate how inherited information can be different from one generation to another and links them back to ideas around generational patterns which they see. An idea of a family tree activity in WISE would be one where students observe and interact with a dynamic animation that shows them the inheritance pattern that occurs across multiple generations of offspring of two human parents. One of the parents would have the trait of widow's peak and the other parent would not have the trait of widow's peak. The students would then see that the parent with the widow's peak has a different color used to represent their genetic information than does the parent with no widow's peak, indicating that each parent has different inheritable information. The next animation would show that the first generation of offspring of these two parents all had widow's peak. Then, the students would see in the last animation how some of the offspring in the second generation of offspring in the family tree have widow's peak and while others do not. Students will then be able to make the connection to how different inherited information from the parents caused the variability in hairline in the second generation. This family tree activity in WISE would further help students make the connection to the WFP and the driving question of the unit: "Why do plants of the same species vary in how they look?" This in turn will unpack even more how that inherited information is different and can allow students to further make more connections and see more patterns.

11 | CONCLUSIONS

This study contributes to the need (Duncan et al., 2009) for a better understanding of upper elementary students' thinking and learning around the concepts of *inheritance of traits* and *variation of traits*. Such an understanding would serve to support instruction at higher levels. It also sheds light on the connections that young students make about generational patterns in their learning about heredity-related ideas. Deepening researchers' and educators' understanding of how students learn about these topics should enable them to better prepare students to be successful in secondary coursework related to complex genetics-related ideas, such as the microscopic processes of cell division and gene expression, as well as the relationship between these processes and inherited characteristics. Further studies should focus on designing curriculum that helps develop students' science practices, particularly constructing science explanations, and on providing more opportunities for students to develop these practices in school science classes. It is also important for future research to consider investigating ways to help teachers, on the front lines of instructing students, unpack and implement these practices, as well as convey the core ideas of *inheritance of traits* and *variation of traits*.

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APPENDIX: GRADE-5 ASSESSMENT AND RUBRIC

1. Madison has a pet dog. Which of the following characteristics did the dog most likely inherit from its parents?

A. A torn ear.

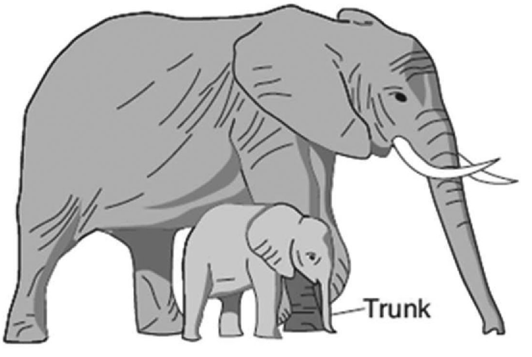
B. The tricks it does.

C. The color of its fur.

D. The place where it lives.

Ideal Response			
C			
Rationale for choosing the item			
To find out if students can identify an inherited trait.			
Rubric for Question 1			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**No answer**	Blank	
0	**Incorrect response**	Student chooses A, B or D	
1	**Correct response**	Student chooses C	

2. The picture below shows a baby elephant with one of its parents.



The baby elephant's trunk is an example of _______.

A. a response to the environment

B. an inherited characteristic

C. a characteristic to attract mates

D. a seasonal adaptation

Ideal Response			
B;			
Rationale for choosing the item			
To find out if students can identify an inherited trait.			
Rubric for Question 2			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**No answer**	Blank	
0	**Incorrect response**	Student A, C or D	
1	**Correct response**	Student chooses B	

3. David's grandparents spoke Spanish and learned English when they came to the United States. Just like his grandparents and his parents, David also speaks both Spanish and English. Did he inherit the skill to speak both Spanish and English?

Please explain your answer.

Ideal Response			
Speaking a particular language is a learned trait, rather than an inherited trait.			
Rationale for choosing the item			
To find out if students can identify a learned trait.			
Rubric for Question 3			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK Off Task
0	**Irrelevant** Students have irrelevant normative or/and non-normative ideas in a given context.	Student claims that knowledge of languages is inherited. OR Off task – write something that is not relevant to the item OR student repeats the question	
1	Isolated Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	Student claims the knowledge of a first language is inherited, but that extra languages must be learned OR Student says that knowledge of a particular language is BOTH inherited and learned. OR Student correctly answers “No” to the question of whether of whether David inherited the skill of speaking these two languages, but does not explain that the skill must have been learned.	
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	Student shows complete understanding that David did NOT inherit the ability to speak Spanish and English because languages must be learned. OR Student identifies the ability to learn language as inherited, but that knowledge of individual languages is acquired.	

4. Some wild flowers need bees for pollination. One summer, there were no bees. What does this mean in terms of wild flowers’ life cycle?

Ideal Response			
This means that the wild flower will stop at the adult stage and will not create any seeds because there were no bees to pollinate the flowers.			
Rationale for choosing the item			
To find out if students understand the role of insects in pollination process of the life cycle.			
Rubric for Question 4			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK
0	Students have irrelevant normative or/and non-normative ideas in a given context.	Off task – write something that is not relevant to the item OR student repeats the question Student response does not accurately describe the life cycle and/or student says there will not be any effect to pollination process if there are no insects. Student response indicates that the wildflowers die or that pollination is needed for the wildflower to live.	
1	**Isolated** Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	Student correctly responds that the flowers will not create seeds, but does not explain why. Student correctly identifies that the species will die out. Student correctly explains the life cycle, but does not mention the role of insects in pollination to create seeds OR Vice versa	
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	Student shows complete understanding of the role of insects in pollination during the life cycle and explains why the wild flower does not produce seeds.	

5a). A son inherits traits ____________.

A. only from his father

B. only from his mother

C. from both his father and his mother

D. from either his father or his mother, but not from both

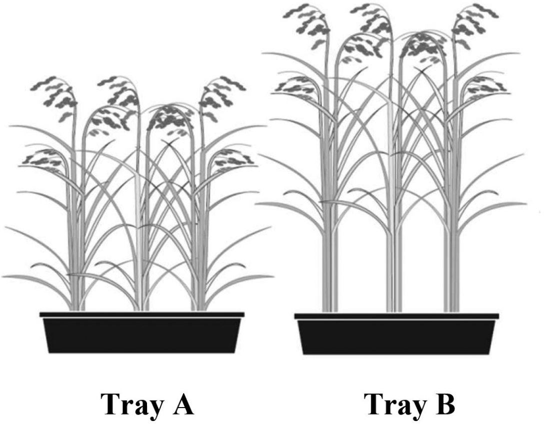
5b). Explain how the son inherits traits based on your answer choice above.

Ideal Response			
C; Parents contribute genetic information/alleles/genes to offspring. The combination of information/alleles determines the offspring's traits. OR During reproduction, each parent contributes genetic information/alleles to the offspring.			
Rationale for choosing the item			
To find out if students understand how parents contribute genetic information to offspring.			

Rubric for Question 5

Score	KI Explanation	Description	Example of student work
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK
0	**Irrelevant** Students have irrelevant normative or/and non-normative ideas in a given context.	A, B or D; No explanation OR Incorrect explanation OR Off task – write something that is not relevant to the item OR student repeats the question	
1	**Isolated** Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	C; No explanation OR Incorrect explanation, e.g. (Get hair from Mom and eyes from Dad) A, B or D; you get genetic information from both parents.	
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	C; Parents contribute genetic information/alleles/genes to offspring and no mention of traits or reproduction	
3	**Complete KI** Students understand how two scientific concepts interact in a given context. Elaborate a scientifically valid link between two relevant normative ideas to a given context.	C; Parents contribute genetic information/alleles/genes to offspring. The combination of information/alleles determines the offspring's traits. OR During reproduction, each parent contributes genetic information/alleles to the offspring.	

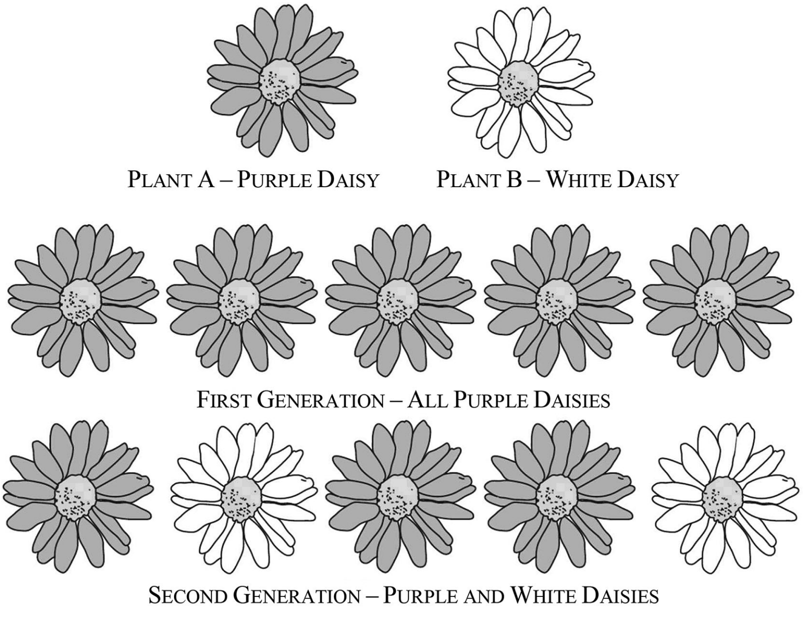
6. The seeds of the plants in Tray A and Tray B came from the same parents. They were planted at the same time, but were kept in different areas of a room.



What are the at least TWO possible explanations for the differences in the plants' height?

Ideal Response			
Tray B is higher than Tray A because Tray B received more sunlight (and water) than Tray A.			
Rationale for choosing the item			
To find out if students understand that inherited traits can also be affected by the environment.			
Rubric for Question 6			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK Off Task
0	**Irrelevant** Students have irrelevant normative or/and non-normative ideas in a given context.	Student talks about number of plants in tray causing height differences or other non-environmental factors OR Off task – write something that is not relevant to the item OR student repeats the question	
1	**Isolated** Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	Student attributes height difference only to inheritance of traits OR Student attributes height difference to the environment but is not specific (i.e. sunlight, shade, nutrients, water)	
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	Student attributes height difference to at least two aspects of the environment (sunlight, shade, nutrients, water)	

7. Plant A is a purple daisy and plant B is a white daisy. The first generation of offspring is purple. The second generation has some purple and some white flowers.



Explain why the second generation has some white daisies.

Ideal Response			
Having white flowers is a recessive trait. The offspring in the first generation were carriers (heterozygous). Some flowers in the second generation got two recessive alleles for flower color.			
Rationale for choosing the item			
To find out if students understand that variation of traits is a result of the combination of dominant and recessive alleles contributed from parents to offspring.			
Rubric for Question 7			
Score	KI Explanation	Description	Example of student work
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK
0	**Irrelevant** Students have irrelevant normative or/and non-normative ideas in a given context.	Student attributes appearance of white daisies to environment. OR 50/50 chance that the flower would be white. **OR** Off task – write something that is not relevant to the item OR student repeats the question	
1	Isolated Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	Skipped a generation OR Inherited white flowers from grandparent OR Inherited flower color from parent OR White is the less common flower color OR Purple is the more common flower color	
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	White flowers are recessive trait. OR Purple flowers are dominant trait. The white flowers inherited recessive alleles. OR The purple flowers inherited dominant alleles/genes.	
3	**Complete KI** Students understand how two scientific concepts interact in a given context. Elaborate a scientifically valid link between two relevant normative ideas to a given context.	Student shows complete understanding that having white flowers is a recessive trait. The offspring in the first generation were carriers (heterozygous). Some flowers in the second generation got two recessive alleles for flower color.	

8. Susan has a miniature (short) female poodle and standard (tall) male poodle. These two poodles had two standard poodle puppies and two miniature poodle puppies.

Circle the statement that is TRUE.

A. The standard poodle puppies inherited height from the dad.

B. The miniature poodle puppies inherited height from the mom.

C. All four poodle puppies inherited height from both parents.

D. Height is not an inherited characteristic.

Ideal Response

C

Rationale for choosing the item

To find out if students understand that both parents contribute genetic information to offspring.

Rubric for Question 8

Score	KI Explanation	Description	Example of student work
M	**No answer**	Blank	
0	**Incorrect response**	A, B, D	
1	**Correct response**	C	

Use the following information to answer questions 9 and 10.

Maria and John both have dimples. They have a daughter named Katie. Katie has no dimples.

9. How is it possible for two parents with dimples to have a child with no dimples?

Ideal Response

Not having dimples is a recessive trait. Both Katie's parents are carriers (heterozygous) of the no dimples allele and both gave her the recessive allele.

Rationale for choosing the item

To find out if students understand that different inherited information accounts for variation of traits.

Rubric for Question 9

Score	KI Explanation	Description	Example of student work
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK
0	**Irrelevant** Students have irrelevant normative or/and non-normative ideas in a given context.	Katie is adopted. OR 50/50 chance Katie would have dimples Katie didn't get that trait from her parents. OR Off task – write something that is not relevant to the item OR student repeats the question	
1	**Isolated** Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	Katie inherited the no dimples trait from her parents. OR The no dimples trait skipped a generation OR She got the no dimples trait from her grandparents (or other relative)	

Ideal Response			
Not having dimples is a recessive trait. Both Katie's parents are carriers (heterozygous) of the no dimples allele and both gave her the recessive allele.			
Rationale for choosing the item			
To find out if students understand that different inherited information accounts for variation of traits.			
Rubric for Question 9			
Score	**KI Explanation**	**Description**	**Example of student work**
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	Students specify not having dimples is a recessive OR having dimples is dominant with no specific mention of what Katie inherited from her parents. OR Katie received the no dimples allele from both parents (with no mention of dominant/recessive alleles).	
3	**Complete KI** Students understand how two scientific concepts interact in a given context. Elaborate a scientifically valid link between two relevant normative ideas to a given context.	Not having dimples is a recessive trait. Both Katie's parents are carriers (heterozygous) of the no dimples allele and both gave her the recessive allele.	

10. Katie grows up and marries Alan. Alan does not have dimples. Then they have children. Will their children have dimples? Why or why not?

Ideal Response			
Their children will not have dimples because not having dimples is a recessive trait and Katie and her husband both have the recessive trait.			
Rationale for choosing the item			
To find out if students understand that			
Rubric for Question 10			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK
0	**Irrelevant** Students have irrelevant normative or/and non-normative ideas in a given context.	Yes, her children will have dimples OR Skipped a generation OR They might inherit it from their grandparents. OR 50/50 chance they might have dimples OR Off task – write something that is not relevant to the item OR student repeats the question [Mention if Katie's husband (their dad) has dimples]	
1	**Isolated** Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	Her kids will not have dimples and no explanation OR Her kids will not have dimples and incorrect explanation OR Her kids will not have dimples because that is an inherited trait.	

Ideal Response			
Their children will not have dimples because not having dimples is a recessive trait and Katie and her husband both have the recessive trait.			
Rationale for choosing the item			
To find out if students understand that			
Rubric for Question 10			
Score	**KI Explanation**	**Description**	**Example of student work**
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	Their children will not have dimples because Katie and her husband don't have dimples.	
3	**Complete KI** Students understand how two scientific concepts interact in a given context. Elaborate a scientifically valid link between two relevant normative ideas relevant to a given context.	Their children will not have dimples because not having dimples is a recessive trait and Katie and her husband both have the recessive trait. Student may mention that because both parents are homozygous recessive, they do not have a dominant allele to pass on.	

11. George is a white cat and Hilda is a black cat. George and Hilda have four kittens: one black, one white, and two gray. Information for color is inherited.

Circle the statements that are TRUE.

A. The gray kittens inherited their color from both parents.

B. The black kitten inherited its color only from the mom.

C. The white kitten inherited its color only from the dad.

D. All four kittens inherited the color from both parents.

Ideal Response			
A & D			
Rationale for choosing the item			
To find out if students understand that both parents contribute genetic information to all offspring.			
Rubric for Question 11			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**No answer**	Blank	
0	**Incorrect response**	Student only chooses B and/or C	
1	**Partially correct response**	Student only selects A or D OR Student selects A and/or D as well as other responses	
2	**Correct response**	Student only selects A & D	

12. This is a diagram of a mature flower.

Mature Flower

This mature flower produced seeds that grew into plants that also have flowers. Which flower is most likely an offspring of this mature plant?

a. **Circle the flower**.

A B C D

b. **Please explain your answer**.

Ideal Response

C ; The offspring inherited the petal shape from the parent. OR C is the flower that looks most like the parent.

Rationale for choosing the item

To find out if students understand that parents contribute genetic information to offspring.

Rubric for Question 12

Score	KI Explanation	Description	Example of student work
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK
0	**Irrelevant** Students have irrelevant normative or/and non-normative ideas in a given context..	A, B or D; No explanation OR Provides incorrect explanation e.g., both plants are tall, they look the same. OR write something that is not relevant to the item OR student repeats the question	
1	**Isolated** Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	C; no explanation OR incorrect explanation, e.g. both plants are tall. A, B or D; Correct explanation: Flower petal shape is inherited OR they have similar petal shape.	
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	C ; The offspring inherited the petal shape from the parent. OR C is the flower that looks most like the parent.	

13. Two male tigers are brothers. They have the same parents, but one of the brothers has dark brown stripes and the other brother has light brown stripes.

Explain why the tigers have different-colored stripes even though they are brothers.

Ideal Response			
The tigers have different colored stripes because their parents passed down different genetic information to each brother (tiger).			
Rationale for choosing the item			
To find out if students understand that parents contribute genetic information to offspring.			
Rubric for Question 13			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK
0	**Irrelevant** Students have irrelevant normative or/and non-normative ideas in a given context.	The tigers are not brothers, one is adopted. 50/50 chance of dark or light stripes. One is darker (or lighter) because it spent more time in the sun or attributes difference to other environmental factors.	
1	**Isolated** Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	Attributes stripe color to being inherited from a particular parent (e.g. mom – light, dad – dark stripe) The tigers get genetic information from both parents OR attributes trait to grandparents (skips a generation).	
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	The tigers have different colored stripes because their parents passed down different genetic information to each brother (tiger).	

14. Which of the following **TWO** processes occur in all living organisms? **Circle your answers.**

A. Reproducing

B. Making food

C. Growing

D. Learning

E. Moving

Ideal Response			
A & C			
Rationale for choosing the item			
To find out if students understand that living organisms grow and reproduce.			
Rubric for Question 14			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**No answer**	Blank	
0	**Incorrect response**	Any other incorrect answer choice or combination of incorrect answer choices	
1	**Partial correct response**	A & other choice OR C & other choice OR A & C and other choice OR just A or just C	
2	**Correct response.**	A & C	

15. Some show dogs have their tails "bobbed" or cut off when they are young. When they grow up and have puppies, will the puppies be missing their tails as well?

Please explain your answer.

Ideal Response			
No, the puppies will not be missing their tails, because the parent dogs inherited the traits of having tails and will pass that trait on to their offspring; the trait of not having tails is acquired.			
Rationale for choosing the item			
To find out if students understand that traits that are acquired by a parent are not passed down to their offspring.			

Rubric for Question 15

Score	KI Explanation	Description	Example of student work
M	**Blank /Invalid**	Blank – no writing at all Invalid – symbol or IDK	I : ?, IDK Off Task
0	**Irrelevant** Students have irrelevant normative or/and non-normative ideas in a given context.	Student claims that puppies will be missing their tails. OR Off task – write something that is not relevant to the item OR student repeats the question	
1	**Isolated** Have relevant normative ideas but fail to recognize links between them. Make links between relevant and irrelevant normative ideas.	Student correctly identifies that the puppies will not be missing their tails, but provides no explanation OR Student correctly identifies that the puppies will not be missing their tails, but says the trait of not having tails is inherited. OR Student identifies that the puppies will be missing their tails, but says the trait of not having tails is acquired. Student correctly identifies that the puppies will be born with a tail because it is an inherited, but assumes the puppies will acquire the same trait as their parents did.	
2	**Partial KI** Have relevant normative ideas but do not fully elaborate links between them in a given context.	Student correctly says that puppies will not be missing their tails, AND shows complete understanding that the reason of puppies will not be missing their tails is because traits that are acquired by a parent are not passed down to their offspring	

16. Which of the following determines the shape of a maple leaf?

(A) The shape of the leaves of the parent plants.

(B) The amount of water in the soil.

(C) The minerals in the soil.

(D) The wind in the area the plant grows.

Ideal Response			
A			
Rationale for choosing the item			
To find out if students understand that parents contribute genetic information to offspring.			
Rubric for Question 16			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**No answer**	Blank	
0	**Incorrect response**	B, C or D	
1	**Correct response .**	A	

17. Crows are black birds that live for six to seven years in the wild and are known for their excellent hearing. Some crows open hard-shelled nuts by dropping them in front of moving cars. **Which of the following characteristic is learned?**

- **A.** Having excellent hearing.
- **B.** Living six to seven years.
- **C.** Dropping nuts in front of cars.
- **D.** Having black feathers.

Ideal Response			
C			
Rationale for choosing the item			
To find out if students understand what a learned trait is.			
Rubric for Question 17			
Score	**KI Explanation**	**Description**	**Example of student work**
M	**No answer**	Blank	
0	**Incorrect response**	A, B or D	
1	**Correct response**	C	