Middle School Students' Reasoning about Biological Inheritance: Students' Resemblance Theory

Viola Manokore & Michelle Williams

Norquest College 10215 108 St NW Edmonton AB T5J 1L6, Canada

Viola.Manokore@norquest.ca

Michelle Williams College of Education Michigan State University East Lansing, MI 48823

mwilliam@msu.edu

Abstract

This study investigates middle school students' reasoning about biological inheritance via examining students' responses to online curricula scaffolding support prompts. A total of 250 seventh-grade students participated in the study and completed a web-based unit on genetics. Students' responses to these prompts were examined to determine whether students held the conceptions about genetic inheritance commonly reported in literature, in addition to being scored for scientific accuracy. Where possible, attempts were made to identify whether students were using evidence from the instructional materials or from their out-of-school experiences in their responses to the prompts. It was evident that approximately half of the students considered traits of offspring to be inherited directly and solely from whichever parent they resemble for that characteristic, rather than viewing it as the result of the interaction of alleles contributed equally by both parents. The term students' resemblance theory was used to refer to this conception. We argue that students' resemblance theory may be used to explain students' thinking when they incorrectly believe that same-sex inheritance of characteristics (e.g., mother/daughter or father/son) to be more prominent. Specifically, we argue that students' resemblance theory may influence students' learning and understanding of Mendel's Law of Segregation.

Key words: biological inheritance, Mendelian, resemblance, genetics

Introduction

According to the American Association for the Advancement of Science (AAAS, 2001), scientific literacy involves both the ability to make connections between science ideas and the acquisition of knowledge about methods of inquiry. As a result, the main goal of school science is to support learners toward becoming scientifically literate through their participation in scientific discourses (McNeill & Krajcik, 2009). One of the key elements of scientific discourses is the ability to construct scientific explanations that consist of a valid claim supported by appropriate evidence (McNeill & Krajcik, 2006, Sadler, 2004; Sandoval & Reiser, 2004). This study is part of a larger study designed to help fifth- through seventh-grade students participate in scientific discourses by using evidence to support claims as they learn about genetic inheritance. In this study, we examine students' responses to prompts that were embedded in a web-based seventh-grade heredity curriculum unit called "From Genotype to Phenotype." We refer to these embedded assessment items as curricula scaffolding support prompts.

In recent years, there have been considerable advances in genetics research achieved through the use of modern science and technology (Duncan & Reiser, 2007; Lewis & Wood-Robinson, 2000; Trumbo, 2000; Venville, Gribble & Donovan, 2005). For example, modern genetics is central to the research on and understanding of contemporary issues in biomedical sciences such as cloning and genomics (Tsui & Treagust, 2007). Despite the importance of genetics in areas such as genomics, cloning, genetic modification of agricultural products, and biomedical sciences, genetic concepts remain challenging to learn from both conceptual and linguistic perspectives (Tsui & Treagust, 2007). The difficulties around this topic suggest not only that genetics concepts are abstract, but also that the "genetics language" itself is highly specialized and presents challenges for students to comprehend.

Furthermore, although genetic inheritance and developmental biology are at the core of conceptual biology (Moore, 1993), the teaching and learning of these concepts continue to pose challenges in the field of biology education (Banet & Ayuso, 2000; Lewis & Wood-Robinson, 2000; Slack & Stewart, 1990). This implies that the understanding of developmental biology and genetic inheritance is critical to the understanding of the fundamental conceptions of biological sciences. In other words, learners need to understand genetic inheritance concepts in order to conceptualize biology. However, students continue to experience challenges in understanding the core of conceptual biology (Banet & Ayuso, 2000).

There is considerable research that highlights problems typically encountered by students as they learn about heredity (Banet & Ayuso, 2000; Kargbo, Hobbs, & Erickson, 1980; Lewis & Kattmann; 2004; Venville et al., 2005; Authors, in press; Wood-Robinson, 1994). National standards and research in science education have demonstrated the importance of supporting students in developing an integrated understanding of the reproduction process and of cell growth and development in order for them to develop a coherent understanding of heredity (AAAS, 2001; Lewis, Leach, & Wood-Robinson, 2000; Authors, in press).

More specifically, research on student understanding of heredity and related concepts has revealed that many students lack insights into the invisible processes that link organisms' genotypes to their phenotypes (Banet & Ayuso, 2000; Kara & Yesilyurt, 2008; Lewis & Wood-Robinson, 2000; Slack & Stewart, 1990; Wood-Robinson, 1994). Lewis and Kattmann (2004) further argue that some students hold beliefs that can interfere with their learning of heredity concepts. For example, these authors illustrate that students often equate genes to traits and are unable to distinguish between phenotypes and genotypes. Moreover, much of the existing research on genetics focuses on secondary students' understandings of the topic, as well as primary students' conceptions of inheritance and kinship (Duncan, Rogat, & Yarden, 2009; Venville et al., 2005). Research is needed on how middle school students (including upper-elementary grade students) understand genetics concepts (Duncan & Tseng, 2010; Venville et al., 2005).

Clough and Wood-Robinson (1985; 1994) in particular have done a great deal to further our knowledge about students' ideas around heredity. Findings from their work show that students have a number of non-normative ideas about genetic inheritance. For example, their research indicates that many students have difficulties understanding the equal contribution of both parents in the formation of the genotype of their offspring (Banet & Ayuso, 2000; Clough & Wood-Robinson, 1985, 1994; Kargbo et al., 1980; Authors, in press). In particular, these researchers (Clough & Wood-Robinson, 1985) found that there was a common belief held by many students that the maternal genetic contribution was greater than the paternal contribution, or in some cases that it was the only contribution inherited by an offspring. Richards (2000) pointed out that the lay knowledge of inheritance is grounded in concepts of kinship and resemblance in families. Nevertheless, whilst there has been a lot of research on lay knowledge about genetics, we still do not know a lot about how the knowledge of kinship may influence students' reasoning about Mendelian inheritance.

Research has also shown that students have difficulty understanding concepts related to dominance and recessiveness, and the distinction between genes and alleles (Banet & Ayuso, 2000; Clough & Wood-Robinson, 1985; Collins & Stewart, 1989; Slack & Stewart, 1990). Some researchers argue that students struggle with understanding genes, alleles, and chromosomes, which makes understandable the fact that some students can neither interpret the concepts of heterozygous and homozygous nor comprehend the probability concept associated with genotypic and phenotypic frequencies in offspring (Banet & Ayuso, 2000; Slack & Stewart, 1990).

In addition to demonstrating students' difficulty in learning heredity concepts from both linguistic and conceptual perspectives (Tsui & Treagust, 2007), research has shown that students have difficulty constructing scientific explanations (Bell & Linn, 2000; McNeill & Krajcik, 2006; Sadler, 2004; Sandoval & Reiser, 2004). Students' ability to construct scientific explanations is important in the discourse of science, as it is tied strongly to school science's goal of science inquiry.

However, little is known about how students integrate their knowledge as they learn how to construct scientific explanations when responding to curricula scaffolding support prompts (McNeill & Krajcik, 2006). It is important to map how students build on their prior knowledge as they interact with school science (Fisher & Moody, 2000). Therefore, it can be useful to understand whether students draw on evidence from their out-of-school experiences or science class experiences to support scientific claims. To that end, in addition to exploring seventh-grade students' responses to scaffolding support prompts that were embedded in a Web-Based Integrated Science Environment (WISE) curriculum unit on genetic inheritance, attempts were made to identify possible sources of the prior understandings used to support those responses. Identifying some sources of students' evidence may be a key step towards characterizing how students build on their prior knowledge as they form new knowledge webs. Specifically, the purpose of this paper is to explore students' reasoning about genetic inheritance. The main research questions that guided the analysis were:

- What are particular conceptions middle school students have about genetic inheritance in relation to Mendel's Law of Segregation?
- Where do students draw evidence from when supporting their scientific claims – in-school or out-of-school experiences?

Thus, understanding students' reasoning around heredity-related ideas such as dominance and recessiveness, the relationship between genes and alleles, and the processes of meiosis can contribute to a discourse on designing appropriate instructional materials and on practices that may promote student learning and understanding about genetic inheritance.

Theoretical Framework

The design of the WISE module "From Genotype to Phenotype," was guided by the knowledge integration (KI) perspective as described by Linn and Hsi (2000). KI views learners as adding ideas to their repertoire and reorganizing their knowledge (Linn, 1995; Linn, Eylon, & Davis, 2004). In particular, this perspective takes on a socio-cognitive frame, thus positing that learning is influenced by both individual construction of knowledge and by social supports such as collaborative learning situations between students and peers or teachers (Linn et al. 2004). This perspective also suggests that students sort out their ideas as a result of instruction, experience, observation, and reflection (Linn & Hsi, 2000). Simultaneously, students may find themselves in situations where they integrate different and sometimes competing academic and everyday funds of knowledge (Moje et al., 2004). Moje et al. (2004) refer to knowledge integration and discourses drawn from different sources as the construction of a 'third space' or 'hybrid space' that emerges from the integration of the 'first space' (discourses encountered outside of school) and 'second space' (discourses encountered in school).

In this study, attempts were made to identify whether students drew from their first space, their second space (the WISE genetic inheritance curriculum unit, in this case), or both spaces in their responses to the embedded scaffolding support prompts. It is important to consider where students draw evidence from as they support their claims, especially when these students have competing ideas. Students are most likely to support their claims using evidence that they find plausible, rather than simply what they are told is accurate. Fisher and Moody (2000) argue that "students' ideas can be so well established and satisfying to them that they tend to be reluctant to replace them with scientific ideas" (p. 57). Drawing on Moje et al.'s (2004) aforementioned theory, students' on-line responses represent the third space. Analysis of students' responses allowed us to identify the space from which students were most likely to have drawn evidence to support their claims as they responded to the embedded scaffolding support prompts. .

Hybridity theory, as described by Moje and her colleagues, acknowledges that students may draw from different sources and also recognizes the convolutions of examining students' everyday funds of knowledge. Hence there is a need for better understanding of students' out-of-school ideas about science concepts so as to develop strategies that effectively enable students to map, merge, and integrate their new biology concepts (Venville et al., 2005).

Methods

Research context

This study was implemented in a Midwestern suburban school district. Two-hundred-fifty seventh grade students participated in the study. The participating school was the only middle school in the district. As was indicated on the school's website, the ethnic makeup of the middle school student body was 7% Latino, 9% Asian, 18% African American, 60% Caucasian, and 6% other. The materials were implemented by two seventh-grade science teachers in a general education classroom setting over a six-week period during the fall of the 2009-10 school year.

Background on teachers

We briefly describe the two middle school teachers' professional backgrounds and the professional supports provided to them prior to and during the WISE project run. Ms. Adams is an experienced African-American teacher who was very motivated to implement a Web-based Inquiry Science Environment (WISE) module in her classroom. Prior to implementing the WISE "From Genotype to Phenotype" unit, Ms. Adams had 27 years of classroom teaching experience. She holds a Master's degree in Elementary Education with an emphasis in English and literacy. Dr Perry is an experienced Caucasian male teacher who had 41 years of teaching experience prior to implementing the WISE genetic inheritance project. He holds a PhD in science education, along with a Bachelors degree in Biology.

WISE "From Genotype to Phenotype" Unit

The WISE "From Genotype to Phenotype" unit was developed by a research partnership comprised of teachers, science education researchers, and a scientist. Table 1 summarizes the curriculum activities.

Table 1. *Summary of Activities in the WISE "From Genotype to Phenotype" Unit*

Activity	Description
Activity 1 Introducing WISE	Introduces students to features of the WISE learning environment.
Activity 2 Will you help us solve a mystery?	Introduces students to the genetic inheritance unit and the driving question for the project. Students are shown a photograph of one parent plant and the first generation of offspring, but they are not told about the genotype of that parent in the photograph nor the phenotype or genotype of the other parent.
Activity 3 Inherited and acquired traits	Introduces the idea of "traits" as characteristics of organisms. The activity solicits students' prior knowledge on traits. Students are asked to distinguish between inherited and acquired traits of plants and animals.
Activity 4 The mechanisms of sexual reproduction	Students learn about sexual reproduction as reproduction involving two parents. Students are introduced to the process of meiosis. In this activity, students are also introduced to Mendel's pea experiment.
Activity 5 Looking more closely at sexual reproduction	Students learn about sexual reproduction in plants, and the use of Punnett squares to determine the genotype and phenotype of an organism.
Activity 6 Sexual and asexual reproduction	Scaffolds students in comparing and contrasting sexual and asexual reproduction, including discussing various advantages and disadvantages of each.
Activity 7 Plant and animal cells	Introduces students to the idea of that all living things are made up of cells, which are compared to building blocks. Students also learn about cell structure and function..
Activity 8 What are the traits of the Fast Plants parent?	Students determine which Fast Plant trait is dominant and which is recessive, and they also determine the genotype of the second offspring generation of Fast Plants; finally, students are asked to determine both the phenotype and genotype of the missing parent plant.

Students observed three generations of Wisconsin Fast Plants in the unit in order to unravel a mystery of parenthood – “What is the second parent’s phenotype for the stem color trait?” At the onset of the project, students were shown a photograph of one purple-stemmed parent plant but were not told that this parent had a dominant expression for the stem color trait. Students were also shown the first generation of offspring, all of which shared the parent’s phenotype of purple stem color. The students actually grew the second generation of Fast Plants, which had both green and purple stems. As students observed the second generation of offspring, they had an opportunity to learn about Mendel’s Law of Segregation. By the end of the unit, students were expected to understand the following Mendelian principles: (1) genes exist in more than one form, (2) offspring inherit two alleles for each trait, (3) allele pairs separate during meiosis, and (4) alleles can be recessive or dominant.

Data Sources and Analysis

The primary data source for this study was students’ online responses to embedded scaffolding support prompts. Both qualitative and quantitative data analysis methods were used in this study. Students’ responses to all scaffolding prompts (44 questions) were scored using a KI rubric adapted from Linn, Lee, Tinker, Husic, and Chiu’s (2006) work. To assess inter-rater reliability, a science education researcher who was familiar with the rubric and experienced in scoring the seventh-grade assessments randomly scored 20% of the responses. The inter-rater reliability was 93%.

Table 2 shows an example of a KI rubric, including examples of student responses for each score.

Table 2. *Example of the Knowledge Integration Rubric*

WISE Embedded Assessment Question
Is it true or false that boys inherit more traits from their fathers than mother? Please explain your answer
Ideal response

“False, offspring inherit half of the genetic material from each parent. Each sex cell has half the number of chromosomes doe to meiosis. Union/joining of sex cells results in an offspring with a full set of chromosomes, half from each parent.”			
Score	KI Explanation	Description	Example of Students work
0	No answer / off task	Blank/Doesn’t make an attempt to answer the question Repeats the question	“I do not know.”
1	Incorrect	Student writes incorrect response indicating a misconception.	“It's True that boys inherit more traits from their fathers more than they do their mothers.”
2	No KI Students have isolated ideas or a mixture of normative and non-normative ideas	Student gives a general/vague response.	“I think it is false but I do not know why.”
3	Partial KI Normative ideas without elaboration	Student shows knowledge that offspring inherit from both parents but does not elaborate.	“False, because boys can inherit from both of their parents not just their dad.”
4	Complete KI Normative ideas with elaboration	Student demonstrates knowledge that offspring inherit half of their genetic material from each parent.	“False, offspring inherit half of the genetic material from each parent. Each sex cell has half the number of chromosomes due to meiosis. Union/joining of sex cells results of an offspring with a full set of chromosomes, half from each parent.”

In addition to giving a quantitative score (to the 44 embedded prompts), responses to scaffolding prompts assessing students’ understanding of concepts related to Mendelian inheritance were qualitatively analyzed and used as examples of students’ reasoning in this paper. We examined students’ responses for the accuracy of their claims and for their use of appropriate evidence as they elaborated on their scientific explanations. In addition, attempts were made to identify the most likely source of the evidence used in students’ explanations – that is, whether students were drawing from their first or second space. However, we acknowledge the complexity of accurately identifying the source of students’ conceptions unless their response is suggestive of a clear source. We also traced students’ explanations to responses so as to map out any relationships between their responses to questions related to Mendelian inheritance. Students’ responses were not lumped into categories – that enabled us to trace their reasoning and thinking as they responded to different questions related to

Mendelian inheritance. In other words, we wanted to examine relationships between students' responses to specific questions.

Results

We assessed results from 250 seventh-grade students to determine what particular conceptions middle school students have about inheritance in relation to Mendel's Law of Segregation, as well as whether students draw on evidence from their out-of-school experiences or science class experiences to support claims made in response to the WISE embedded scaffolding support prompts.

Passage of Genetic Material

In this section, we examine student conceptions around a number of heredity-related ideas, including the inheritance genetic material from both parents and the intersection of gender resemblance and genetic inheritance.

Inheriting genetic material from both parents. The first scaffolding support prompt asked students to indicate examples of traits that they inherited from their parents (refer to Table 3). As outlined by the rubric, students scored a 0 if they did not respond to the question and scored a 1 if they displayed non-normative ideas, such as listing an acquired trait. Apart from mentioning traits, there was no explanation required for this particular item. Also, Item 1 did not specify the number of heritable features students should list. Since this question did not require students to provide an explanation, the maximum possible score was a 3 for specifying at least two inherited traits.

In addition to listing the features, some students also provided explanations for their reasoning. However, there was no KI score given for the explanations because the question did not require such information. Nevertheless, it is important to note that some students associated a particular feature with a particular parent. For example, some students stated that they inherited 'nose shape from my mother' or 'eye color from my father.' This finding prompted us to explore further whether students taught by different teachers had a similar pattern of responses. Researchers randomly selected a class from one seventh-grade teacher, then chose a corresponding hour from the other.

Table 3. *Examples of Students' Responses to WISE Embedded Assessment Item 1 (Ms. Adams' Second Hour Class)*

Item 1 What are some traits that you have inherited from your parents? Ideal response Eye color, skin color, natural hair color and texture, freckles, dimples, PTC (Phenylthiocarbamide) tasting	
Students' Responses Pre-activity responses (score)	Comment
Pair 2A1 My partner has black hair from her dad, and brown from her mom. She has really dark brown eyes like both her parents. I have hair from my mom and blue eyes from my mom. (3)	These students are attributing inheritable features to a specific parent. In their response, they mention at least 2 heritable traits. They were using their out-of-school funds of knowledge (the parent they look like) to explain their claims.
Pair 2A2 I have inherited my brown eyes from my mom and my partner inherited athletic abilities from parents. (2)	This pair had a mixture of normative and non-normative ideas. Their response indicates a belief that athletic abilities can be genetically passed on from parents to offspring. In addition, they were using their out-of-school funds of knowledge to explain their claims.
Pair 2A3 My hair looks like my dad, and my eye color like my mom. I have eyes like my dad. (3)	This response shows how students attribute certain traits to individual parents. This pair used their out-of-school funds of knowledge (the parent they look like) to explain their claims.
Pair 2A4 My eye color and my hair color are two traits I have inherited from my parents. (3)	This pair correctly listed two inherited traits.
Pair 2A5 I have brown hair like my mom, I have the same nose as my mom. (3)	The student mentions two traits that resemble her mother, an out-of school experience being used to explain the response.
Pair 2A6 My friend has brown hair, blue eyes are some traits I have inherited from my mom and dad I have inherited blonde hair from my mom, and tallness from my dad. (3)	One of the pair attributes height to his dad and hair color to his mother. The pair used their out-of-school observation to support their claims.
Pair 2A7 I am short from my mom and eye color from my dad. I have short legs from my dad and freckles from my mom. (3)	This pair attributed certain inheritable traits to a specific parent and indicator that they are using their out-of-school funds-of-knowledge
Pair 2A8 The ability to roll my tongue – my partner I have two different colored eyes. (2)	Though this pair correctly list inheritable traits, it is not clear what they mean by having two different colored eyes
Pair 2A9 I have inherited my looks and my blue eyes from my dad.	This response was vague because it was not clear what was meant by 'looks.' The eye color was attributed to a parent an

(2)	indication of use of out-of-school experiences and observations.
Pair 2A10 Eye color and hair color (3)	This pair list two traits that can be inherited from parents.
Pair 2A11 I have brown hair, straight hair, freckles. She has brownish blonde hair, hazel eyes, straight hair (3)	Each of the students in this group listed the traits they inherited from their parents.
Pair 2A12 Hair colors, freckles, eye colors. (3)	The students listed inheritable traits.
Pair 2A13 Blank (0)	This pair did not respond to both scaffolding support prompts
Pair 2A14 J has Freckles, eye color, height and S has eye color, height, musical ability (3)	The students included both acquired traits and heritable traits that are influenced by the environment.
Pair 2A15 Yes, skin color, hair, and height. (3)	Students list heritable traits

Although students were not required to explain their responses (as mentioned above), about 50% of the students in Ms. Adams' class attributed an inheritable trait to a specific parent (see examples of student responses in Table 3). As shown in Table 4, there was a similar pattern of responses for students in Dr. Perry's class. Across both teachers' classes, approximately 50% of students used their out-of-school funds of knowledge (observation of resemblance between themselves and a parent) to explain their responses to Item 1. In other words, students relied on their first space as they created their third, hybrid space (refer to Tables 3 and 4).

The aforementioned results indicated that students from both teachers' classes had similar patterns of responses that attributed certain traits to a specific parent. To further verify this finding, a second class from each teacher was randomly selected to have their responses analyzed. It was apparent across all the classes that were analyzed that the students did not fully understand how alleles are passed from parents to offspring. Thus, attributing a heritable trait to a specific parent may influence the way students understand how parents with a dominant expression for a certain trait may have children that are different from both parents for this trait.

Table 4. *Examples of Students' Responses to WISE Embedded Assessment Item 1 (Dr. Perry's Second Hour Class*)

Item 1
What are some traits that you have inherited from your parents?
Ideal response
Examples are eye color, skin color, natural hair color and texture, freckles, dimples, PTC (Phenylthiocarbamide) tasting.

Item 1. Pre-activity	Comment
Pair 2P1 J-straight hair from my dad, the same color eyes as my dad. I also have my mom's mouth. A-wavy hair from my mom and brown hair from my mom. Also same nose from my mom. (3)	Though the students identified inherited traits, they attribute the traits to a specific parent – a conclusion based on their out-of-school observations and funds of knowledge.
Pair 2P2 N- I have inherited my parents singing and my moms hair and my dads lips my moms nose and my dad's butt that's pretty much it. C- I have inherited my mom's singing umm my dad's hair line, umm my mom's nose and eyes, umm my dad's lips umm that is pretty much it. (2)	The students also listed traits that can be learned such as singing, and they attributed all heritable traits to specific parents – a conclusion based on their out-of-school observations and funds of knowledge.
Pair 2P3 Blank (0)	This pair of students did not respond to either prompt.
Pair 2P4 Fast growing nails, brown eyes, and brown skin. P- light brown eyes, brown hair, white skin (3)	The pair listed fast growing nails both before and after the activity, despite the fact that nail growth can also be influenced by diet.
Pair 2P5 Blank (0)	The students did not respond to the scaffolding prompts.
Pair 2P6 Hair, skin and teeth (2)	This pair is simply listing traits without elaboration. The students did not specify whether they meant hair color or skin color.
Pair 2P7 Dark skin, brown eyes, curly hair (3)	Students correctly listed inherited traits.
Pair 2P8 A- eye color, face J- dad's eye color, dad's skin color (3)	Although the pair listed inherited traits, they attributed them to a specific parent.
Pair 2P9 I inherited brown eyes from both parents and dark hair from my dad (3)	The response indicates that one of the student's eye color looks like that of both parents' – based on their out-of-school observations and funds of knowledge.
Pair 2P10 Hair color, eye color, skin color, height, and health conditions. (3)	It was not clear what the students meant by 'health conditions,' although they may have been referring to inherited diseases. Also, height, though inherited, it is also influenced by the environment
Pair 2P11 A- bad eyes, small, hair brown eyes J- brownish/blondish, hair smarts, good looks, green eyes (3)	This pair listed inheritable traits, though they included some features that were worded somewhat ambiguously, such as "good looks," "small," or "smarts."
Pair 2P12 Your hair texture and color, eye color, and skin color. (3)	This pair clearly listed traits that can be inherited.

Pair 2P13 *R*- head structure, hair color, eye color M- nose structure, eye color, hair color (3)	These students listed three traits heritable from parents.
Pair 3P14 Brown Eyes- Dad Mixed Skin- Both Brown Hair- Dad Height- Mom Speed- Both (3)	It was surprising that it was only the skin color that the pair mentioned as mixed and from both parents. Other than that, they attributed the rest of the heritable traits to specific parents - based on their out-of-school observations and funds of knowledge

Based on further analysis of students' responses, seventh-graders demonstrated a partial understanding of the mechanisms of inheritance, particularly the fact that offspring inherit alleles from both parents. This was true even after they interacted with the WISE heredity unit. It can be deduced from students' responses that many believe each parent contributes 'genes' for particular traits. While students may realize that they inherit features from both parents, many struggle to understand that the expression of each phenotype is dependent on two alleles, one from each parent.

Students' resemblance theory. The resemblance theory emerged from the data. Students who attributed a heritable trait to a specific parent seemed to believe that offspring inherit traits only from the parent they resemble for that feature, as if each parent passes on genes for different traits. Additionally, some mixed race students (see example Table 4 pair 3P14) recognized their skin color as having been inherited from both of their parents, but not the other traits listed. Such reasoning from students suggests that they believe that traits are inherited from whichever parent they most resemble for that particular trait. It can be inferred that these students might have been drawing on their everyday observations and experiences to construct such explanations about genetic inheritance.

Attributing inherited traits to a specific parent may seem plausible to students based on their observations of resemblance to a specific parent. In this study, we refer to such attributions as students' '*resemblance theory.'* Students who subscribe to this theory tend to believe that an offspring inherits a trait from a parent whom they resemble (thus '*resemblance* *theory'*), this belief forming a large portion of their understanding of genetic inheritance. Students who identify a specific parent from whom they inherited a particular feature are likely basing their explanations on their out-of-school funds of knowledge.

This conceptual understanding may serve to explain why many students rationalize that boys inherit more traits from their fathers and girls from their mothers– they may believe that there is more resemblance between parents and offspring of the same gender. Such reasoning may influence the kinds of hybrid spaces students create, as well as their understanding of how heterozygous parents may have a homozygous recessive offspring for a particular trait.

Gender resemblance and genetic inheritance. Items 2 and 3 were designed elicit student ideas around gender resemblance and inheritance by asking first if boys inherit more traits from their fathers, and then the same of girls and mothers. Table 5 depicts the frequencies for each score to Items 2 and 3. Using the KI rubric, students were given a score of 1 if their answer contained non-normative ideas. For example, students would score a 1 if they indicated that it was true that boys inherited more genes from their fathers.

Table 5. *Frequencies of Students' Ideas on Gender Resemblance and Inheritance*

KI Scores	Item 2. Is it true or false that boys inherit more traits from their fathers than from their mothers? Please explain your answer		Item 3. Is it true or false that girls inherit more traits from their mothers than from their fathers? Please explain your answer	
	Frequency	%	Frequency	%
0	24	16.6	28	19.3
1	38	26.2	37	25.5
2	47	32.4	45	31.0
3	23	15.9	22	15.2
4	12	8.3	12	8.3

While many students did display partial or complete knowledge integration, there were a sizeable number of students who still had difficulty understanding how gender resemblance affected inheritance of traits between parents and offspring.

Table 6 shows examples of students' responses to scaffolding support prompts regarding how boys and girls inherit traits from their fathers and mothers. Research indicates some students believe that boys inherit more of their features from their fathers while girls inherit more from their mothers (Berthelsen, 1999).

Table 6. *Examples of Students' Responses to WISE Embedded Assessment Items 2 and 3*

Item 2
Is it true or false that boys inherit more traits from their fathers than from their mothers? Please explain your answer.
Item 3
Is it true or false that girls inherit more traits from their mothers than from their fathers? Please explain your answer.
Ideal response
False, offspring inherit from both parents. They get half from the mother and the other half from the father. Meiosis produces sex cells that have ½ chromosome number, when sex cells unit during reproduction the resulting offspring end up with a full set of chromosomes.

Item 2. response	Item 3. Pre activity response	Comment
Pair 2A1 Z-True- all boys are strong and look like their fathers (1) S-False- my brother inherited more traits from my mother (2)	Z-True- I look more like my mom (1) S-False- I look like both (2)	One of the students said it was true that boys and girls inherit more from their fathers and mothers, respectively. However, though the other student said it was false. The explanation does not show understanding that offspring inherit traits equally from both parents.
Pair 2A2 IDK (0)	IDK (0)	This pair indicated that they did not know on the pre-activity item, and they did not attempt the post-activity item. However, in their response to item 1 they attributed features to a specific parent.
Pair 2A3 We think this is true because they are of the same gender, so they will inherit the boyish	We think this is true because girls will inherit the girlish traits from their	This pair believes that boys do inherit more from their fathers, and girls from their mothers. They explain that girls get girlish looks from mothers.
Traits from their father (1)	Mother (1)	Such interpretation does not show understanding of how sex determining genetic information is passed from parents to offspring.
Pair 2A4 False because it is a 50-50 chance because if your mom has a dominant gene and you are a boy then you would still get a dominant gene whether from your mother or your father (3)	False for the same reason as above (False because it is a 50 – 50 chance because if your mom has a dominant gene and you are a boy then you would still get a dominant gene whether from your mother or your father (3)	Though this pair explained that offspring inherit traits from both parents, they seem to suggest that it is only the dominant alleles that are passed on. It can be inferred from this response that this pair believes that it is the dominant allele that is passed on to and expressed in offspring.

Pair 2A5 False, children inherit traits equally from each parent (4)	False, children inherit traits equally from each parents regardless of sex (4)	These students show understanding that offspring inherit from both parents.
Pair 2A6 I do not think that this is false because you should get an even number of traits from both parents (2)	I do not think that this is false because you should get an even number of traits from your parents (2)	The students' explanation suggests that they have some idea that traits are inherited from both parents. They have a mixture of normative and non-normative ideas demonstrated by their response, which suggests that they believe that boys inherit more from their fathers than their mothers.
Pair 2A7 I do not know because my brother looks a lot more like my mother (2)	I do not know but I look like my dad more than my mom (2)	The student draws from their personal family experiences that their brother resembles their mother more than their father. The student observed some cross gender resemblance.
Pair 2A8 I think this is true because (1)	Blank (0)	This student believes it is true that boys inherit more from their fathers but did not explain their thinking.
Pair 2A9 I do not think so because you get your genes from both your mom and your dad (3)	I do not think so, again you have genes from both parents (3)	Student does not elaborate on parental equal contribution for each trait
Pair 2A10 False because you inherit equal parts from both parents (3)	False because you inherit equal parts from both parents (3)	The pair gives a correct response, although it is not very clear what they mean by 'equal parts.'
Pair 2A11 We have agreed (my partner and I) that we are not sure (0)	We have agreed (my partner and I) that we are not sure (0)	These students did not know the answer to the scaffolding prompts.
Pair 2A12 Well, it is most likely not true because everyone has an even chance of getting the same gene as another family member female or male (2)	The possibilities can even out between two parents because of this girls can look and act like their mother or their father (2)	Students show mixture of ideas and seem to suggest that the way people 'act' could be inherited.
Pair 2A13 True (1)	Blank (0)	Though they did not elaborate, this pair believes that it is true that boys inherit more from their fathers than their mothers.
Pair 2A14 No, they receive traits from both their mom and dad. Maybe sometimes more than the other but not necessarily always (2)	No, they receive traits from both their mom and dad. Maybe sometimes more than the other but not necessarily always (2)	Response indicates that students have limited understanding of how traits are passed on from parents to offspring.
Pair 2A15 True because he is a boy and he is most likely to have more inheritance they are the same gender (1)	True because the girl is same gender as her mom (1)	These students believe that gender resemblance has something to do with inheriting 'more' from one parent.

As shown in Table 5, a sizeable number of the students (25.5-26.2%) believed that children inherit more traits from their same-gender parent, thus receiving a score of 1. Most interestingly, all students who stated 'true' for Items 2 and 3 also in Item 1 attributed to a specific parent certain traits that they have inherited. In other words, their explanations of inheritance were based on their out-of-school observations of resemblance between parents and children.

Additionally, a significant number of the seventh-graders (31.0-32.4%) received a KI score of 2, suggesting that students held a mixture of normative and non-normative ideas. Specifically, students indicated that the notion that boys inherit more traits from their fathers than their mothers is false, but went on to suggest that it is 'the dominant gene that gets to be passed on.' Such a response suggests that these students believe that only dominant alleles are passed from parents to offspring and that all phenotypic appearances are due to dominant alleles. Together, these students (those receiving KI scores of 1 or 2) form a majority who all had some difficulty understanding how traits are passed on from each parent to their offspring.

Some responses point to students' difficulty comprehending issues of parental resemblance (including gender), the passing on of recessive and dominant alleles, and how these issues relate to genetic inheritance from both parents. Findings imply that students formed their explanations using out-of-school funds of knowledge based on their life experiences and observations. For example, observations about hair color, eye color, and gender resemblance to a particular parent helped form students' belief that a specific parent whom they resembled for a trait was the only parent passing on the alleles to control that trait. This is likely due to students' difficulty visualizing the abstract phenomenon of genetic inheritance, in which contribution from both parents exists and is important, despite the child only resembling one parent for a specific inheritable trait (or neither parent, in cases where both parents are heterozygous for a trait, while the offspring is homozygous recessive). For example, students may fail to comprehend how a female offspring may have received a sex-determining allele from her male parent, or vice versa. Such explanations from students are not random or arbitrary but rather represent a pattern that is plausible to the learners as they try to make sense of the world using their limited scientific knowledge (Fisher & Moody, 2000).

Students' Conceptions of the Relationships between Genetic Structures, Genotype, and Phenotype

In addition to examining students' understandings of the passage of genetic material across generations, we also chose assessment items to enable us to explore students' ideas around the relationships between genetic structures within an organism, as well as that organism's genotype and phenotype. For example, Item 7 was designed to elicit students' ideas as they reflected on science concepts learned through interaction with the WISE unit. Table 7 illustrates examples of students' responses to Item 7.

Table 7. *Examples of Students' Conceptions of Genes and Alleles as they Relate to Genotype and Phenotype*

WISE Embedded Assessment Item 7

How are an organism's genes and alleles related to its genotype and phenotype?

Ideal response

Alleles are different forms of genes. A gene is a functional unit of heredity. Genotype is the genetic make-up of an organism whereas phenotype is the physical appearance of an organism as determined by its genotype and/or the environment.

Students' responses	Comment
Pair 5P1 They are related because they are directly responsible for the external appearance (phenotype) and the genes (genotype). The genes and alleles vary between parent genes but alleles contain multiple possibilities for traits to occur in the offspring (3)	Though the student shows some understanding, the explanation does not show comprehensive conceptual understanding and relationships between concepts, especially with regard to the relationship between genes and alleles.
Pair 5P2 They are related because they each bear the outcome of the way something someone or how a person is going to come out in life. Like eyes can be totally different from their parents or they can have the same features of their parents. Recessive gene cannot be real gene without another recessive gene and the dominant gene is a dominant gene that is a gene just with one (2)	The students confuse 'gene' and 'phenotype.' They seem not to understand alleles or their role in genotype and phenotype expression.
Pair 5P3 An organisms' gene determines its genetic traits, the organisms' alleles are the genes of its parents, combining both alleles gives information to what genes contains and its phenotype (2)	The students have isolated ideas about the relationship between genes, alleles, genotype, and phenotype .
Pair 5P4 Genes make up the genotype and phenotype and alleles are the gene types. Example, the genotype make up what genes are in the body making a person who they are. Phenotypes are the genes that people can see like eye color, hair color and skin color (2)	The response does not show coherent understanding of the concepts. The student seem to suggest that a gene is the same as phenotype.
Pair 5P5	Students have isolated ideas about the

Genes and alleles are related because genes and alleles are the traits and genotypes and phenotypes are how they are categorized. For example, someone has the alleles and phenotype for brown eyes (2)	relationship between concepts of genes, alleles, genotype and phenotype.
Pair 5P6 The genes are related to genotype because they hold the trait. They make the genotype possible. The alleles are related to genotype because the alleles hold the different versions of the trait, for example the rose gene has the alleles for red color and white petal color that the plant could have RR, Rr or rr. The genes are related to the phenotype because the genes hold the alleles that determine what the phenotype is. The alleles are related to the phenotype because they contain the information that determines the phenotype (2)	The students illustrate an understanding of alleles but do not show coherent understanding of genotype and phenotype as they relate to genes and alleles.
Pair 5P7 Genes and alleles make the genotype, and the phenotype is the end that comes out how you are going to look (3)	The students show understanding of genotype and phenotype, though they do not distinguish between genes and alleles.
Pair 5P8 Genes determine alleles and genotypes determine phenotypes. Without the genes, the alleles would not matter or exist. Genotypes are every similar to genes too. The phenotype is part of a gene. It is the color that makes the genes what they really are (2)	Students show a mixture of ideas and fail to provide a coherent relationship. Students do not understand the difference between genes and phenotype
Pair 5P9 If you look at the word genotype, you see first 3 letters gen. Alleles is the color of the plant. The first letters of that is pen. The three genotypes are, I am using the letter R: RR. Rr and rr. Here is an example: organisms could have a mother and father that have two offspring. The first offspring have a genotype of Rr. The second has rr. They are different. (2)	The students demonstrate a lack of understanding of the relationship between genes, alleles, phenotype and genotype. They are confusing allele and phenotype. Though the response is rather confusing, they scored a 2 because the pair attempted to explain using an example on color of flowers that was in the unit.
Pair 5P10 Genes and alleles are related to genotypes and phenotypes. Genotypes and phenotypes are related to genes and alleles by the fact that genotypes are organism's particular amount of alleles, which are different types of genes and phenotypes are the way traits are shown as expression of the organism. Traits are like genes, so I guess that is how they are related (2)	Students show isolated ideas about the relationship between the concepts of genes, alleles, genotype and phenotype.
Pair 5P11 Blank (0)	There was no attempt to respond to the question

While a gene can be viewed as a basic instruction for the formation of an organism, an allele is a variation of that instruction. Analysis of the students' responses indicates that they had difficulty distinguishing between genes and alleles. Although most students successfully defined genotype, a majority of them were still unable to explain the relationship between alleles, genotype, and phenotype. Students' limited understanding around the relationship between these concepts may affect the way they explain the mechanisms of the passage of genetic material from parents to offspring. Although the students were discussing unseen or abstract concepts such as genes and alleles, they continued to draw from their observations and experiences. For example, a pair with a mixture of normative and non-normative ideas stated "phenotypes are the genes that people can see like eye color, hair color, and skin color." This response shows a limited understanding of genes, and the examples provided by the students relate to their own out-of-school observations.

Just as students struggled to relate the concepts of genes, alleles, genotype, and phenotype, they also experienced difficulty in developing an accurate understanding of the relationship between genes, chromosomes, and DNA. Item 9 addressed this understanding, and Table 8 below shows some examples of students' responses to this assessment item. Deep knowledge on the aforementioned concepts may enable students to gain some understanding on how alleles are passed from parents to offspring.

Table 8. *Examples of Students Responses to Item 9*

Item 9 What is the relationship between chromosomes, genes, and DNA? Ideal response DNA are the molecules that make genes. A gene is the unit of heredity and is a segment of a chromosome. Genes make up the chromosomes. A chromosome is a thread that holds many genes.	
Students' Response (KI score)	Comment
Pair 5P1 Genes contain specific types of information and are in chromosomes. DNA is the raw, precise data in the chromosomes. DNA also known as the double helix, basically makes up the chromosome. Chromosomes are compact structures used for carrying DNA and contain cells and DNA (3)	The student pair shows some understanding of the relationship but does not really elaborate on what genes are in relation to chromosomes. It was not clear what the pair meant by chromosomes containing cells; maybe they intended to say genes.
Pair 5P2 DNA is basically how they are related. DNA is a collection of molecules. Chromosomes are a compact for carrying DNA cells. Genes are contained in chromosomes. A gene is a section of DNA strand that provides specific information needed for a specific trait (4)	This pair gave a nearly complete response but also mention what they call 'DNA cells,' rather than DNA molecules. This suggests that students may be confusing cells with molecules.
Pair 5P3 Blank (0)	This pair did not respond to item 9.
Pair 5P1 Chromosomes and genes are two parts of DNA (1)	This pair does not understand the relationship between these concepts. They seem to suggest that a chromosomes is part of DNA molecule.
Pair 5P4 DNA is your genetic information. It carries the information needed to give you your traits. Genes are contained in chromosomes. Chromosomes are for carrying both DNA and genes and that's how they are related. (3)	Though the students show conceptual understanding, they did not distinguish between gene and DNA.
Pair 5P5 Chromosomes contain genes and genes contain DNA (4)	The response suggests that the pair have a conceptual understanding of the relationship between chromosomes, genes, and DNA.
Pair 5P6 The chromosomes are made up of cells, and cells are made into genes, and genes consist of DNA (2)	This pair seems not to understand what cells are, though they stated that genes consist of DNA.

Pair 5P7 Your genes in your chromosomes and your chromosomes are basically your DNA (2)	This pair views chromosomes, genes, and DNA as the same thing.
Pair 5P8 Chromosomes are in DNA strands. DNA is the strands that store the 46 pairs of chromosomes that we have. Genes are also in DNA strands (1)	This pair shows limited understanding of the relationship between chromosomes, genes, and DNA.
Pair 5P9 Well chromosomes are a combination of DNA and genes are contained in chromosomes (2)	The students' response shows that they have some idea about the relationship between genes and chromosomes but have a vague understanding on the relationship between DNA and genes.
Pair 5P10 Blank (0)	This pair did not respond to the item.

As shown in Table 8, some students had difficulty distinguishing between chromosomes, genes, and DNA. This may be because of the way these terms are used in society at large. For example, phrases such as 'it is in your genes' and 'it is in your DNA' are often used to refer to an individual's inborn traits or to their similarity to their family (Nelkin & Lindee, 2004). Rather than using evidence from the WISE unit to make their claims, a sizeable number of students continued to use their out-of-school observations and experiences to respond to the scaffolding support prompts embedded throughout the unit, even as they neared the end. The majority of students attributed certain inheritable features to a specific parent, and some showed limited knowledge around the relationships between genetic structures and the concepts of genotype and phenotype.

In sum, many students struggled when attempting to understand genetic concepts and the ways in which genetic information is passed across generations. It became evident through students' responses to the scaffolding support prompts that their out-of-school funds of knowledge influenced their learning of these concepts – for instance, as in the *resemblance theory* described above. It is clear that students' insistence on drawing from their out-of-school funds of knowledge contributed to their difficulty in understanding the invisible, microscopic processes and structures associated with heredity. As previously discussed, students who rely on this *resemblance theory* tend to conflate the concepts of gene, allele, and genotype and have a limited understanding of the ways that these relate to observable phenotype or to the passage of genetic material from parents to offspring. Relatedly, these students also face challenges in understanding that all traits come from both parents – that is, that both mother and father provide genetic information that contributes to determining an offspring's characteristics. These students focus on observable similarities between parent and offspring, making it difficult for them to comprehend how a parent without such a visible resemblance to its offspring might still have played a part in determining its characteristics or how two parents who are heterozygous for a particular trait could have a child who is homozygous recessive and thus does not seem to resemble either parent. Figure 1 illustrates how students' conceptions relate to their *resemblance theory* and to principles of Mendel's Law of Segregation.

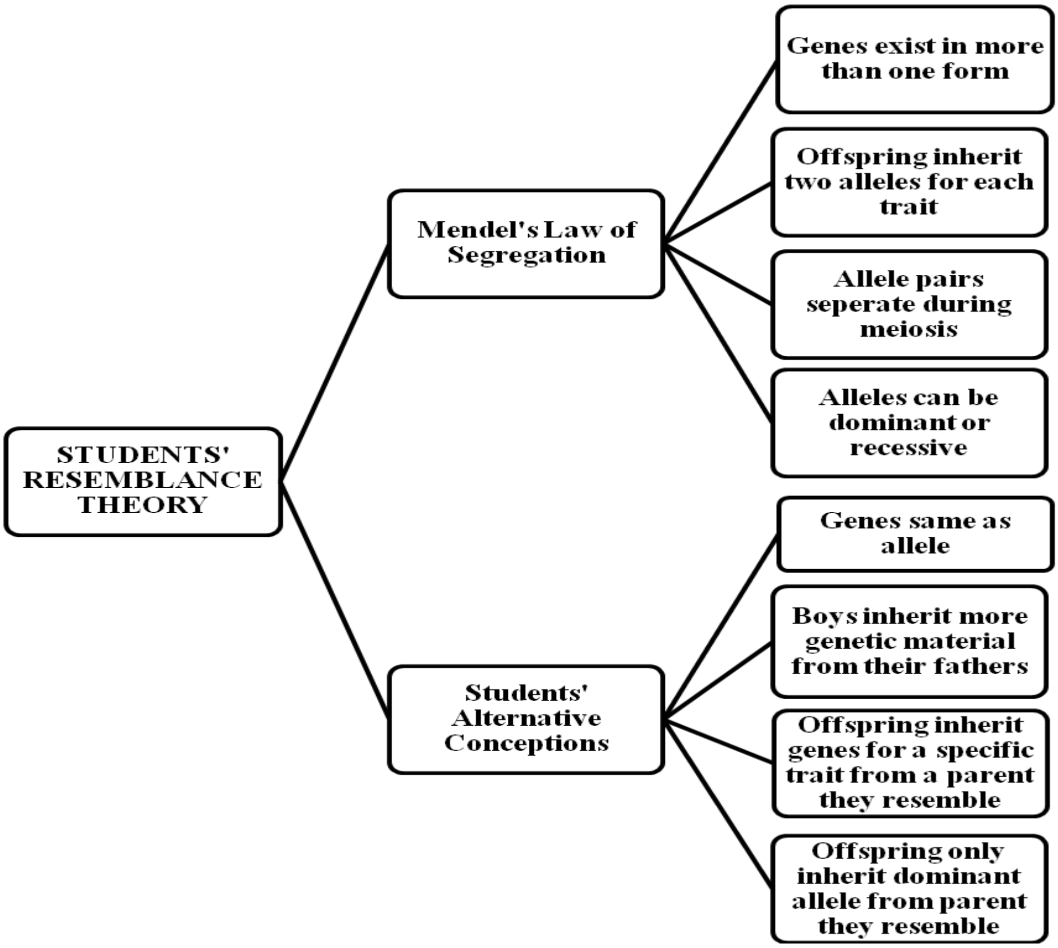

Figure 1. Students' *Resemblance Theory* and Mendel's Law of Segregation

The gap between students' expected and actual understandings is clear. As an example, Mendel's Law of Segregation requires students to understand that genes exist in more than one form, yet some students seem to struggle with distinguishing between genes and alleles. Also in contrast to Mendel's Law of Segregation, students that exhibit the *resemblance theory* believe that offspring inherit more genetic material from their parent of the same gender. Additionally, students for whom belief in the *resemblance theory* influences their scientific understandings tend to believe that only dominant alleles contribute to appearance and that an offspring inherits dominant alleles for particular traits from the parent they resemble for those traits. Such ideas can hinder students' comprehension of the principles of Mendel's Law of Segregation.

Discussion And Conclusions

As findings show, students seem to rely on a variety of sources for experiences and ideas regarding genetic inheritance as they develop their conception of the topic (Nelkin & Lindee, 2004; Venville et al., 2005). It is important to note that some of these sources do not portray genetic information in the same way that it is understood in the scientific world. As a result, students can have diverse funds of knowledge with widely different depictions of DNA, and a number of these may compete with school science. The hybridity theory can apply to the integration of competing and non-competing knowledge and discourses (Moje et. al., 2004).

Learning environments need to have activities that challenge students' out-of-school funds of knowledge that may interfere with the integration of different funds of knowledge in hybrid spaces as students build on prior understandings. Moje et al. (2004) have argued that because science is a highly specialized area with many assumptions about what counts as scientific knowledge, the idea of integrating in- and out-of-school funds of knowledge becomes challenging. In this study, we argue that learning environments that challenge or build on students' *resemblance theory* may enable students to make connections between their first and second spaces. That way, students may be able to integrate their in- and out-of-school funds of knowledge and create scientifically robust hybrid spaces.

Implications

This study proposes that students' attribution of inherited traits to a specific parent they resemble for that trait can be termed "students' *resemblance theory*" and that students' *resemblance theory* may influence their learning and understanding regarding Mendel's Law of Segregation. This study shows how some students who reason from resemblance standpoint may have their own ways of explaining the principles of Mendelian inheritance.

This study can contribute to the biological education research on students' conceptions about genetic inheritance and the ways in which their conceptions may influence their understanding of scientific concepts, particularly students in the middle grades, about whose conceptions around this topic little is known. One important aspect of students' out-of-school funds of knowledge that may impact their knowledge integration may be students' "*resemblance theory.*" It is possible that it is from this theory that students start to develop their conceptions about genetic inheritance. Based on findings from this study, we recommend that curriculum that builds on students' prior knowledge about genetic inheritance may need to consider activities that challenge their *resemblance theory*. However, more research is needed that examines students reasoning thinking around this theory.

This study may also contribute to science education research on students' knowledge integration in a hybrid space. It was evident in some students' responses that they supported their claims using their out-of-school funds of knowledge even as they built on their prior knowledge with school science. We posit that students' *resemblance theory* plays a role in this difficulty, and that it may be a crucial element in students' formation of hybrid spaces. Hence more research is needed to explore and map out students' *resemblance theory* and how that may impact their learning about genetic inheritance.

References

American Association for the Advancement of Science. (2001). *Atlas of science literacy*. New York: Oxford University Press.

Banet, E. & Ayuso, E. (2000). Teaching Genetics at Secondary School: A Strategy for Teaching about the Location of Inheritance Information. *Science Education* 84 (3), 313-351.

Berthelsen, B. (1999). Students Naïve Conceptions in Life Science. *The Michigan Science Teachers Association Journal,* 44(1), 13-19.

Clough, E. E., & Wood-Robinson, C. (1985). Children's understanding of inheritance. *Journal of Biological Education, 19*(4), 305-310.

Collins, A., & Stewart, J. H. (1989). The knowledge structure of Mendelian genetics. The American Biology Teacher, 51, 143–149.

Duncan, R. G. & Reiser, B.J., (2007). Reasoning Across Ontologically Distinct Levels: Students' Understandings of Molecular Genetics. *Journal of Research in Science Teaching.*

Duncan, R. G., Rogat, A. D., & Yarden, A. (2009). A learning progression for deepening students' understandings of modern genetics. *Journal of Research in Science Teaching, 46*(6), 655-674.

Duncan, R. G., & Tseng, K. A. (2010). Designing project-based instruction to foster generative and mechanistic understandings in genetics. *Science Education, 95*(1) 21-56.

Fisher, K. M. & Moody, D. E., (2000). Student Misconceptions in Biology. In K. M. Fisher, J. H. Wandersee and D. E. Moody. *Mapping Biology Knowledge* (pp. 55-75). Kluwer Acadamic Publishers

Kara, Y. & Yesilyurt, S. (2008). Comparing the Impacts of Tutorial and Edutainment Software

Programs on Students' Achievements, Misconceptions, and Attitudes towards Biology. *Journal of Science Education and Technology* 17:32–41

Kargbo, D. B., Hobbs, D., & Erickson, G. L. (1980). Children's beliefs about inherited characteristics. *Journal of Biological Education, 14*(2), 137-146.

Lewis, J. & Kattmann, U. (2004). Traits, genes, particles and information: re-visiting students' understandings of Genetics. *International Journal of Science Education*, 26(2), 195-206.

Lewis, J., Leach, J., & Wood-Robinson, C. (2000). What's in a cell?—young people's understanding of the genetic relationship between cells within an individual. *Journal of Biological Education, 34(*3), 129-132.

Lewis, J., & Wood-Robinson, C. (2000). Genes, chromosomes, cell division and inheritance-do students see any relationship? *International Journal of Science Education, 22(*2), 177-195.

Linn, M. C. (1995). Designing computer learning environments for engineering and computer science: The scaffolded knowledge integration framework. *Journal of Science Education and Technology, 4*(2), 103-126.

Linn, M. C. (2006). The Knowledge Integration Perspective on Learning and Instruction. In R. K. Sawyer (Ed.), The Cambridge Handbook of the Learning Sciences (pp. 243-264). New York: Cambridge University Press.

Linn, M. C., Davis, E. A., & Bell, P. (2004). *Internet environments for science education.* Mahwah, NJ: Erlbaum.

Linn, M. C., Eylon, B. S., & Davis, E. A. (2004). The knowledge integration perspective on learning. In M. C. Linn, E. A. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 73-83). Mahwah, NJ: Erlbaum.

Linn, M. C., & Hsi, S. (2000). Computers, Teachers, Peers: Science Learning Partners. Mahwah, NJ: Lawrence Erlbaum Associates.

Linn, M. C., Lee, H.S., Tinker, R., Husic, F., & Chiu, J. L. (2006). Teaching and assessing knowledge integration. *Science, 313*, 1049-1050.

Linn, M. C., & Slotta, J. D. (2000). WISE science. *Educational Leadership, 58*(2): 29-32.

Martin Richards (2000). Jack Tizard Memorial Lecture: Children's Understanding of Inheritance and Family. Child Psychology and Psychiatry Review, 5, pp 2-8

McNeill, K. L. & Krajcik, J., (2006). Middle school students' use of appropriate and inappropriate evidence in writing scientific explanations. In Lovett, M & Shah, P (Eds.) *Thinking with Data: the Proceedings of the 33rd Carnegie Symposium on Cognition.* Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

McNeill, K. L. & Krajcik, J. (2008). Scientific explanations: Characterizing and evaluating the effects of teachers' instructional practices on student learning. *Journal of Research in Science Teaching, 45*(1), 53-78.

McNeill, K. L. & Krajcik, J. (2009). Synergy between teacher practices and curricular scaffolds to support students in using domain specific and domain general knowledge in writing arguments to explain phenomena. *The Journal of the Learning Sciences, 18*(3), 416-460.

McNeill, K. L. Lizotte, D.J., Krajcik, J., & Marx, R.W. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. *The Journal of the Learning Sciences.* 15(2), 153-191.

Moje, E. B., McIntosh Ciechanowski, K., Kramer, K., Ellis, L., Carrillo, R., & Collazo, T. (2004). Working toward third space in content area literacy: An examination of everyday funds of knowledge and discourse. *Reading Research Quarterly*, *39*(1), 38-71.

Moore, J. A. (1993). *Science as a way of knowing: The foundations of modern biology.* Cambridge, MA, Harvard University Press.

Nelkin, D., & Lindee, M. S. (2004). The DNA mystique: The gene as a cultural icon. Michigan: The University of Michigan Press.

Quintana, C., Reiser, B., Davis, E. A., Krajcik, J., Fretz, E., Golan, R, Kyza, E., Edelson, D. & Soloway, E. (2004). A scaffolding design framework for designing educational software. *The Journal of the Learning Sciences*, *13*(3), 337-386.

Reiser, B. J., Tabak, I., Sandoval, W. A., Smith, B. K., Steinmuller, F., & Leone, A. J. (2001). BGuILE: Strategic and conceptual scaffolds for scientific inquiry in biology classrooms. In S. M. Carver & D. Klahr (Eds.), *Cognition and instruction: Twenty-five years of progress* (pp. 263-305). Mahwah, NJ: Erlbaum.

Slack, S. J., & Stewart, J. H. (1990). High school students' problem-solving performance on realistic genetics problems. *Journal of Research in Science Teaching*, 27, 55–67.

Stewart, J. H. (1982). Difficulties experienced by high school students when learning basic Mendelian genetics. *The American Biology Teacher*, 44, 80–84, 89.

Trumbo, S. (2000). Introducing students to the genetic information age. *The American Biology Teacher*, 62(4), 259– 261.

Tsui, C-Y. & Treagust, D. F., (2007). Understanding Genetics: Analysis of Secondary Students' Conceptual Status. *Journal of Research in Science Teaching*, 44(2), 205-235.

Venville, G., Gribble, S. J. & Donovan, J. (2005). An Exploration of Young Children's Understandings of Genetics Concepts from Ontological and Epistemological Perspectives. *Science Education*, 89, 614– 633.

Venville, G., & Treagust, D.F. (1998). Exploring conceptual change in genetics using multidimensional interpretive framework. *Journal of Research in Science Teaching*, 35, 1031-1055.

Wandersee, J. H. & Fisher, K. M. (2000). Knowing Biology. In K. M. Fisher, J. H. Wandersee & D. E. Moody (Eds.), Mapping Biology Knowledge (pp. 39-54). Dordrecht: Kluwer.

Wandersee, J. H., Fisher, K. M. & Moody, D. E. (2000). Knowing Biology. In K. M. Fisher, J. H. Wandersee & D. E. Moody (Eds.), Mapping Biology Knowledge (pp. 25-37). Dordrecht: Kluwer.

Authors (in press). From Phenotype to Genotype: Exploring Middle School Students' Understandings of Genetic Inheritance in a Web-based Environment *The American Biology Teacher*.

Wood-Robinson, C. (1994). Young people's ideas about inheritance and evolution. *Studies in Science Education*, *24*, 29-47.

Wood-Robinson, C., Lewis, J. & and Leach, J. (2000). Young people's understanding of the nature of genetic information in the cells of an organism. *Journal of Biological Education*, 35(1), 29-36.