Probing visual literacy skills reveals student conceptions of scale and abstraction with respect to chromosomes

Crystal Uminski[1], Dina L. Newman[1], L. Kate Wright[1]

[1] Thomas H. Gosnell School of Life Sciences, Rochester Institute of Technology; Rochester, NY, 14623, United States.

Manuscript type: Research article

Character count with spaces: 59,240

Short title: Chromosome visual literacy

Corresponding author:
Dina Newman (dina.newman@rit.edu)

Keywords: visual literacy, undergraduate, biology education, drawing, chromosome, chromatid, misconceptions, sketch, visual representations

Abstract

Molecular biology can be difficult for undergraduate students because course content is often taught using highly-abstract visual representations. Genetic concepts can be depicted with lines, letters, shapes, and symbols, and students need to engage their visual literacy skills to appropriately decipher these abstract representations. We previously found that undergraduate course materials almost always represent chromosomes in abstract forms, such as "X" shapes or straight lines with a dot for the centromere. We hypothesized that students struggle to apply their visual literacy skills to accurately interpret these abstract representations of chromosomes, which may be related to the frequently-documented incomplete or incorrect ideas students have about chromosome structure and function. To explore students' visual literacy related to representations of chromosomes, we conducted 35 semi-structured interviews with students who had taken at least a year of biology courses. We asked them to sketch chromosomes, interpret an abstract representation of chromosomes, and use the abstract representation to answer a question about meiosis. We found that 97% of participants (34 of 35) held conceptual errors related to chromosome structure and function. These conceptual errors were often not evident in participants' verbal definitions of chromosomes and were only revealed in their sketches or explanations of their sketches. We found that participants frequently misinterpreted X-shaped representations of chromosomes, mistook unreplicated homologous chromosomes as separated sister chromatids, and held misconceptions related to the structure and function of centromeres. These findings have implications for how chromosomes are taught in biology courses. We recommend that instructors explicitly discuss the conventions and norms of representing chromosomes as a pathway for increasing students' visual literacy in molecular biology.

INTRODUCTION

Molecular biology is often a difficult subject for students because the concepts in the curricula cannot be directly visualized (Johnstone, 1991; Newman et al., 2023). Biologists rely on abstract symbols and shapes to visualize these invisible concepts and often use multiple representations to illustrate the same concept (Kindfield, 1994b; Wright et al., 2022). For example, a gene can be represented as a string of letters, a box-and-line diagram, or a double helix. A trained biologist can easily navigate between such representations, but students often struggle to maneuver between different representations of the same concept (Cho et al., 1985; Newman et al., 2023).

One reason biology students encounter difficulties interpreting different visual representations may be linked to the development of their skills in visual literacy. Visual literacy is the ability to "read" and understand the many different visual representations as well as the ability to "write" and create visual representations of their mental models (Schönborn & Anderson, 2006). Visual literacy skills are necessary to appropriately interpret and communicate using the abstract symbols and shapes in molecular biology (Schönborn & Anderson, 2010; Trumbo, 1999), but these are skills that take time, practice, and scaffolded support to develop (Offerdahl et al., 2017). To develop fluency in visual literacy, students need to not only engage the correct content knowledge relevant to the concept being represented, but also apply the appropriate logical reasoning about the representation and its features and be able to distinguish the relevant visual characteristics and conventions within the representation (Schönborn & Anderson, 2009). Within molecular biology, the development of these visual literacy skills can be constrained by students' abilities to reason across levels of organization (i.e., biological scale)

and their ability to reason across levels of abstraction within visual representations (Schönborn & Anderson, 2009, 2010).

We can better understand how students' visual literacy in molecular biology is related to their conceptions of scale and abstraction in visual representations by operationalizing the scale and abstraction of visual representations within a conceptual framework called the DNA Landscape (Wright et al., 2022). The DNA Landscape categorizes the different representations of DNA in a 3-by-3 matrix to show variation in representations across scale (nucleotide, gene, and chromosome) and abstraction (very abstract, elements of shape and abstraction, and literal shape) (Wright et al., 2022). Students who have fluent visual literacy in molecular biology should be able to understand the relationships between images in the DNA Landscape that are presented at different levels of abstraction and between representations at different scales, but to develop this fluency students need to have previously seen the multiple representations at each scale that are present in the DNA Landscape (Schönborn & Anderson, 2006).

While students are likely to encounter representations from each category within the DNA Landscape matrix in their undergraduate education, previous work using the DNA Landscape identified that students are not likely to see each aspect in the matrix with the same frequency (Wright et al., 2022). For example, textbooks much more often use abstract representations of chromosomes (in the form of lines, Xs, and Os) than more realistic maps or representations of chromatin. We hypothesized this imbalanced exposure might impact students' visual literacy skills related to how they think about chromosomes.

Conceptual knowledge of chromosomes is necessary for students to understand the *Vision and Change* core concept of Information Flow, Exchange, and Storage (American Association for the Advancement of Science, 2011; Brownell et al., 2014), but historically

students often struggle with course content related to chromosomes (Etobro & Banjoko, 2017; Kindfield, 1991; Newman et al., 2012; Saka et al., 2006). Chromosome structure can be a particularly difficult topic for students (Kindfield, 1991, 1994a, 1994b; Newman et al., 2012; Wright et al., 2021), and misunderstandings related to the function and behavior of chromosomes in mitosis and meiosis are so common among students that these concepts are targeted on concept assessments such as the Introductory Molecular and Cell Biology Concept Assessment (Shi et al., 2010), the Genetics Concept Assessment (M. K. Smith et al., 2008), and the Meiosis Concept Inventory (Kalas et al., 2013). Although these misunderstandings are commonly identified in the literature, little work has been done to examine the relationship between how students' misunderstanding of chromosomes may be associated with their visual literacy related to representations of chromosomes (Newman et al., 2023).

We wanted to explore how these common chromosome misunderstandings could be linked to the types of representations students encounter in textbooks and course materials. We hypothesized that the overrepresentation of abstract chromosome images in course media could be hindering their visual literacy and their ability to distinguish the salient features in representations of chromosomes. Thus, we set out to answer the following research question: How are students conceptualizing chromosomes and applying visual literacy skills to interpret abstract images of chromosomes?

METHODS

Participants: We conducted semi-structured interviews with 35 students from two different institutions; a primarily undergraduate institution and an R2 research institution (Table 1). All research participants had completed at least a year of biology coursework. We used several

recruitment methods to achieve a broad sample of participants, including emailing biology majors at each institution, posting flyers in science buildings, and using in-person recruitment during sessions of upper-division biology courses. We also used snowball sampling methods by asking participants to refer their peers to register for the study after they had concluded the interview protocol. Participants consented to this research and were compensated with a $20 Amazon gift card for their participation. Pseudonyms were selected by the participant or assigned by the researcher. This research was approved and classified as exempt from human-subjects review by Rochester Institute of Technology (protocol 01090823).

Interview Protocol: We developed the prompts in our interview protocol to align with two frameworks to target specific visual literacy skills (Table 2). We designed interview prompts to target the factors from the Conceptual-Reasoning-Mode (C-R-M) framework that are associated with the ability to interpret and visualize biological representations (Schönborn & Anderson, 2009, 2010). We wrote our interview prompts in ways that could elicit evidence of participants' conceptual understanding of chromosomes (Conceptual) as well as the cognitive skills participants engaged (Reasoning) to make sense of visual representations (Mode) of chromosomes. The C-R-M framework indicates that there is a minimum amount of prior conceptual knowledge that is necessary for the interpretation of visual representations (Schönborn & Anderson, 2010), so we scaffolded our interview questions to target conceptual understanding before asking participants to reason about the visual representation we presented in the interview. We refined our use of the Reasoning component of the C-R-M model by classifying cognitive skills according to Bloom's Taxonomy (Anderson et al., 2001; Bloom et al., 1956). We used the Visualizing Bloom's Tool (Arneson & Offerdahl, 2018) to design

interview prompts that target visual literacy skills across a range of cognitive skills from Bloom's Taxonomy. As with any prompts or questions designed to target specific cognitive skills, the mental processes that a participant engages may not always align with the targeted cognitive skill level (Monrad et al., 2021).

Our interview protocol used a scaffold structure to prompt research participants to engage in higher-order cognitive skills. We first asked participants to provide a verbal definition of chromosomes and then to draw a chromosome and explain their drawing. Some participants drew additional sketches to supplement their explanations. Next we prompted participants to interpret the illustration that accompanied item #2 from the validated and widely-used Genetics Concept Assessment (GCA; M. K. Smith et al., 2008). The GCA item includes an abstract representation of two pairs of unreplicated homologous chromosomes within a cell. In this representation, the chromosomes are depicted as single vertical lines with large black dots for centromeres, and alleles on the chromosomes are represented using letters (F/f and Q/q). We asked participants to evaluate the effectiveness of the representation of chromosomes and to describe any confusing elements within the representation. Then we asked them to compare and contrast their drawing to the GCA representation. We next provided participants with the full item #2 from the GCA, which includes a written description of the image, explaining that it contains two pairs of chromosomes on which are two different genes and asks them to select the possible sperm genotypes if the cell divides normally. After participants selected their answer from a multiple-choice list, we asked them to draw a picture that represents the option they selected.

We conducted and recorded interviews using the video conferencing software Zoom. Of the 35 interviews, 11 participants (31%) created drawings using the Zoom whiteboard and 24

participants (69%) drew on their own paper and sent us photos or scans of their sketches via email. Audio recordings were transcribed by Otter.ai and then cleaned manually.

This interview protocol was part of a larger interview probing visual literacy across a range of molecular biology concepts. Participants completed the chromosome protocol in approximately ten minutes, while the entire interview was approximately 45 minutes in length.

After 35 interviews, the emergence of new insights or concepts from interviews had slowed, so we judged that we had reached a theoretical saturation of conceptions and reasoning about chromosome structure.

Codebook development: We used initial coding (Saldaña, 2013) to develop our codebook from the interview data. We shared our initial codebook with a group of biology education researchers consisting of two biology professors, two postdoctoral researchers, and four undergraduate students. The group of researchers used the codebook to code one interview transcript that was selected based on a random-number generator. We compared interpretations of the codebook across the members of the research group, discussed areas of disagreement, and subsequently refined our codebook to its present version.

Our codebook consists of sets of codes to categorize participants' verbal definitions of chromosomes, sketches of chromosomes, the accuracy of their description of their sketch, the accuracy of their interpretation of the concept assessment image, the accuracy of their answer to the concept assessment item, and the sketches that represent their response to the concept assessment item.

Verbal definitions of chromosomes: We coded participant's verbal descriptions of chromosomes based on whether they described the shape (e.g. "X-shaped"), structure (e.g. "made of DNA"), and/or function (e.g. "involved in meiosis") of chromosomes.

Sketches of chromosomes: Our coding of chromosome sketches resembles previous classifications of chromosome representations (Kindfield, 1994b), with the addition of three new visual variants. Like Kindfield, we observed participants drawing chromosomes as an X-shape including dimensionality with a centromere (either explicitly included or implied by the X-shape), an X-shape without dimensionality (i.e., two crossed lines) with a centromere (either explicitly included or implied by the X-shape), or an unreplicated chromosome which may or may not have a centromere. Unlike Kindfield, we never observed participants only drawing unreplicated chromosomes with the single straight line representation. The other visual variants included representations of chromosomes as two side-by-side structures (resembling butterfly wings) that lacked a clear centromere structure, as well as representations of chromosomes as coiled lines in both replicated and unreplicated forms.

We also coded participants' chromosome sketches for their level of abstraction based on their location on the DNA Landscape matrix (Wright et al., 2022). We considered the level of abstraction as conventional if the sketch of the chromosome contained elements that were consistent with a single level of abstraction in the DNA Landscape and unconventional when the sketch contained elements across multiple levels of abstraction in the DNA Landscape (e.g., both "very abstract" and "literal shape" within the same representation).

Accuracy of description of sketch: We classified participants' descriptions of their sketches as either correct or incorrect. We coded descriptions of sketches as correct in situations in which participants used the correct vocabulary to describe the elements in their sketch (e.g., correctly

stating that their X-shaped chromosome was a replicated chromosome). We coded descriptions of sketches as incorrect when participants used incorrect vocabulary or concepts to describe their sketch (e.g., identifying an X-shaped chromosome sketch as a pair of homologous chromosomes).

Concept assessment image interpretation: We classified participants' interpretation of the image from the GCA item #2 as either a correct or incorrect interpretation. Correct interpretations indicated that the image consisted of 4 chromosomes or two pairs of homologous chromosomes and that the letters in the image represented genes or alleles. If participants stated any number of chromosomes other than 4, mistook the homologous chromosomes for sister chromatids, or made a statement indicating that the homologous chromosomes should be connected at the centromere, it was coded as incorrect.

Answer to concept assessment: We coded three types of answers to the GCA item #2: the correct answer with the correct reasoning, the correct answer with incorrect reasoning, or an incorrect answer.

Sketches of concept assessment answer: We coded the sketches that participants created of their GCA answer based on their location on the DNA Landscape (Wright et al., 2022). We classified participant drawings by scale (chromosome or gene) as well as level of abstraction. Our coding of level of abstraction for the concept assessment sketches was similar to conventional and unconventional coding we applied to participants' initial sketches of chromosomes with the additional modifications to reflect our observations of new variations of unconventional abstraction in sketches. These unconventional abstractions included unexpected mixings across the levels of scale in the DNA Landscape (e.g., incorrectly mixing gene-scale and chromosome-

scale elements in the same abstract image) as well as unconventional uses of symbols (e.g., misapplication of the letters in Punnett squares).

Interrater reliability: To establish interrater reliability between coders, two members of the research team (CU and LKW) used the codebook to independently code eight randomly selected interview transcripts (23% of the sample). There was 93% agreement between the two raters across 160 coding decisions. The Cohen's kappa coefficient was 0.83, which indicates strong agreement between raters (McHugh, 2012). The two raters discussed any disagreements until consensus.

Positionality: Author CU conducted the interviews and acknowledges the limitations in this research because of the power differential inherent in their position as an education researcher who is older and has more formal education training relative to the interviewees. This power differential may inadvertently reinforce traditional power structures and hierarchies, thereby shaping the ways in which participants perceived and responded to the interview.

All members of the research team are trained in biology education research, have studied visual representations in biology, and have taught courses where we observed students making errors about chromosome structure and/or function. As such, we had preexisting ideas about how research participants might respond which consciously and unconsciously shaped our analysis and interpretation of participant responses.

RESULTS

We conducted 35 semi-structured interviews to understand how students conceptualize chromosomes and found that 97% of participants (34 of 35) demonstrated at least one conceptual error in how they described or drew chromosomes. We frequently found mismatches between participants' verbal statements and their sketches, highlighting that although participants often know the vocabulary words to describe chromosomes, their conceptual knowledge of chromosome structure and function is shallow and pocked with fundamental misunderstandings. We further probed participants' understanding of chromosome structure and function using an item from the Genetics Concept Assessment and found that many struggled to interpret the chromosome diagram. Despite misinterpreting the GCA image, the majority of participants were able to correctly answer the associated concept assessment item; however, when asked to explain their thinking, most participants provided an incorrect line of reasoning to justify their answer.

How do undergraduate students define chromosomes?

We asked participants "What is a chromosome?" and the majority (86%, n = 30) provided definitions related to chromosome structure (Figure 1). Most participants correctly noted structural elements of chromosomes, such as the fact that chromosomes consist of DNA and contain histones. Participants less frequently mentioned chromosome functions (e.g., the role of chromosomes in gene expression or meiosis) or chromosome shape (e.g., an "X" shape), but when they did mention function or shape, it was typically paired with content related to chromosome structure.

Even though participants frequently provided factually correct definitions of chromosomes, we noted several incorrect/unclear ideas within their definitions such as the size and scale of chromosomes. For example, Jimmy (sophomore biotechnology major) stated, "A

chromosome is I guess like a collection of DNA and genes that are…they're like the encapsulation of all your DNA." Jimmy incorrectly implies that a single chromosome contains all the DNA within a cell. In other cases, participants confused the scale of chromosomes and genes. For example, Evelyn (junior biology major) said, "A chromosome is part of the DNA that can lead to a gene," and Mia (sophomore biology major) declared that "A chromosome was basically I think it's like part of the genes."

Additionally, we uncovered incorrect ideas related to chromosome function during cell division. For example, Norma (senior biotechnology major) said, "A chromosome is basically like an X, it can be single, it can also be like the X shape, and it contains genetic information and just I guess, a shaped form. And the DNA can be double stranded—is double stranded—and then if it goes through like the other processes, it could become single stranded and whatnot." While Norma understood that genetic information is divided in "other processes," such as mitosis and meiosis, division does not make DNA a single-stranded molecule.

How do undergraduate students draw chromosomes?

When asked to sketch a chromosome, 100% of participants drew images that aligned to the "very abstract" representation of chromosomes on the DNA Landscape. We observed a wide variation in the types of abstract representations and in participants' justifications about their representational choices. We categorized the variation in participant's initial sketches into five distinct representations of abstract chromosomes: dimensional X-shaped chromosomes, X-shaped chromosomes drawn with overlapping lines, chromosomes represented as side-by-side structures, chromosomes represented with coiled lines, and unreplicated chromosomes (Figure 2).

We found that participants most commonly drew chromosomes in a dimensional X-shape with looping, bubbly shapes used to portray the arms of the chromosome. Evelyn, whose sketch is the exemplar of the dimensional X-shape in Figure 2, described that she drew the chromosome as a "circular thing [so] that you could probably see that there is more like their stuff inside it." For some participants, this dimensionality was a meaningful representation that reflected their understanding that chromosomes are structures that contain "stuff," which we interpret as DNA and proteins.

Most participants who drew the dimensional X-shape chromosome provided explanations that revealed they did not fully understand what the X-shape represents (Figure 3). For example, Nadine (senior environmental science major) describes the X-shape as consisting of "two halves that kind of fit together," but it is unclear how or by what process she thought that this "fit" occurs. In another example, Annie (sophomore biochemistry and molecular biology major) described that her sketch contained "four parts" across two sections of genetic code (Figure 3). When the interviewer asked for clarification about this statement and whether the "two sections" (i.e., the two p-arms in a replicated chromosome) that Annie referenced were identical, she responded "Um, no. So like, for example, if you have like, if you are homozygous it'd be like your Big E and then like the little e like that." Here, Annie is not only confused about the correct vocabulary (i.e., homozygous compared to heterozygous), but conflated sister chromatids (which must contain the same allele) in her drawing with homologous chromosomes (which could have two different alleles).

Participants less commonly represented replicated chromosomes using two crossed lines in an X-shape (without dimensionality). These participants frequently compared this shape to other representations of chromosomes (Figure 3). Even though participants like Pluto

(sophomore general science major) asserted that “everyone knows” the crossed-line chromosome, less than a quarter of participants chose to use this representation in their own drawings.

Three-quarters of participants (n = 24) drew an X-shaped chromosome (with or without dimensionality) in which the centromere was either drawn or implied by the shape of the chromosome. However, we also observed unexpected and unconventional representations of chromosomes as two side-by-side structures that do not overlap. Participants’ rationale for their side-by-side chromosome were highly variable (Figure 3). Alex (senior biology major) drew the side-by-side chromosome with a separate box to represent the centromere. Christin (sophomore environmental science major) referenced a centromere in her explanation of her side-by-side chromosome drawing which did not include a centromere drawn into the image. Mia said that she drew side-by-side chromosomes to resemble X and Y chromosomes. Each of the side-by-side chromosome sketches had unconventional elements of abstraction that signaled a misunderstanding of chromosome structure.

A quarter of participants (n = 9) drew sketches of unreplicated chromosomes and often referred back to the interview prompt, “Can you sketch a chromosome,” in their explanations. For example, before sketching, Josie (junior biochemistry and molecular biology major) asked the interviewer “Should I do like — I'll just do one?” and proceeded to draw a single unreplicated chromosome. Similarly, when the interviewer asked Lacie (junior biotechnology and molecular bioscience major) why she drew an unreplicated chromosome, she referred back to the interview question, “’cause I was like ‘just one chromosome.’” Both Josie and Lacie mentioned their sketches were not reflecting what they “normally” thought about for chromosomes. Josie remarked that “The way I normally picture them is double. Because we

talked about them with like, the replication, but that's—I'm pretty sure they just exist as singles," and Lacie added that "I was thinking, you know, normally in human beings, chromosomes are drawn in pairs." For both Josie and Lacie, "a chromosome" was equivalent to a single-molecule chromosome.

We found three instances of participants using unconventional abstraction in which their sketch contained elements across the DNA Landscape and mixed elements of the abstract shapes with the more literal coiled lines representations (Figure 4). Jack's (senior mechanical engineering major) description of his coiled chromosome that could be "filled" was similar to how participants described their drawings of the X-shape with dimensionality could have "stuff inside." Ristan (senior biochemistry and molecular biology major) first drew an unreplicated chromosome using coils and said "I think that's to sort of show that it's not like one strand." Ristan provided a second sketch of a single line for comparison to better illustrate that his first sketch contained "many, many strands of DNA all compressed on top of each other." Ristan's sketches and explanation seem to erroneously suggest that numerous individual molecules of DNA make up an unreplicated chromosome.

We note that participants sometimes produced the coiled chromosome sketches during follow-up questioning which provided unique insights into their understanding of chromosome structure (Figure 5). Norma's sketch is a more conventional abstraction of a dimensional X-shape as well as an unreplicated chromosome, providing the rationale that the chromosome "becomes an X-shape throughout the process of meiosis." When probed about her choice of these particular representations, Norma produced the follow-up sketch of coiled DNA and said "DNA is just coiled up, so it's like this," suggesting a robust understanding of chromosome structure. Conversely, Teresa's (junior individualized study major) follow-up sketches illustrate a

misunderstanding of chromosome structure. Teresa modified her sketch by filling in the p-arm of the chromosome with the narration that "This is like the clusters of the DNA, big clusters." She stopped at the centromere then continued in a separate pen stroke to fill in the q arm of the chromosome, saying "Yeah, and this is also another cluster of like DNA." Her descriptions and unconventional method of drawing show that she thought of chromosomes as consisting of two separate units of DNA partitioned by the centromere.

While we focus on what participants did draw in their sketches of chromosomes, it is also important to note what they did not draw. None of the participants in our sample drew chromosomes in a circular shape that might resemble bacterial chromosomes. We did not observe any participants drawing chromosomes with banding patterns like a karyotype or drawing a map with positions of genes.

We necessarily focus our results on the errors in visual literacy related to chromosomes, as these errors provide novel insights into student thinking, but we also want to emphasize many participants (63%, n = 22) used appropriate terms and vocabulary to describe the chromosome structure that they drew.

How are undergraduate students interpreting an image of chromosomes?

We found that 71% of participants (n = 25) incorrectly interpreted the image from the concept assessment (Table 3). Participants often demonstrated a mixture of incorrect and incomplete ideas in their interpretations. Participants' difficulty in interpreting the image of chromosomes may be related to their unfamiliarity with the type of abstract representation. Several participants remarked that they had never seen an image like this before, and Donna

(sophomore biology and environmental science major) even noted that "If I saw this, I would not recognize it as a chromosome."

The most common error in interpretation of the image from the GCA was the confusion of homologous chromosomes for chromatids, occurring in 19 of 25 incorrect interpretations. This is exemplified by a quote from a participant who immediately asked "The chromatids aren't paired together?" This confusion of homologous chromosomes and sister chromatids persisted even with the visual scaffolding provided by the heterozygous alleles labeled for each chromosome pair (F/f and Q/q). Maddy (junior biology major) incorrectly used the alleles to justify her interpretation of the image as chromatids, stating that the labeled alleles are "just like to specify that they're the same chromosome but different sister chromatids." Heather (sophomore biotechnology and molecular bioscience major) similarly struggled to differentiate chromosomes and chromatids, stating that "in terms of chromosomes that have already been replicated, there's two. So that would be a total of four." Heather arrived at correct number of chromosomes in the image, but did so by applying the wrong reasoning.

In many cases, this misunderstanding of homologous chromosomes stemmed from the idea that the unreplicated homologous chromosomes in the image were "separated" sister chromatids. Participants tended to view the centromere as the place where the chromatids should have been "paired together" or connected. Numerous quotes (each from a separate participant) illustrates this point:

> "The two halves of the chromosome just pulled apart—Instead of being in that X, they're just portrayed separately" – Eileen (sophomore environmental science major)

"I usually imagine [chromosomes] like connected like I did [in my sketch of a replicated chromosome]. Because they're like separate—might be something that I thought was a little confusing at first." – Quentin (junior biology/pre-med major)

"[The image is] like showing that there's two separate chromatids, and because like on the initial drawing that I drew [this participant initially drew a replicated chromosome], a lot of people would just see it as like one X structure and not like two structures that are together." – Jimmy (sophomore biotechnology major)

"In both sketches [participant sketch and the GCA image], it's made out of two parts and you can kind of see that they're supposed to be attached together with the dots on that sketch and on my sketch." – Sylvia (sophomore biochemistry and molecular biology major)

"Typically, I think they're [the chromatids] kind of fused together, so maybe that's one thing that might be confusing to people [who] just started learning." – Jay (Master's student in bioinformatics)

Other incorrect ideas related to the length of the chromosomes in the GCA representation. One set of the homologous chromosomes in the image (which contained the F and f alleles) are represented with longer arms compared to the second set of chromosomes (which contain the Q and q alleles). Annie conflated the length of the chromosomes with dominance: "Could the longer strands mean it's dominant?" Another participant, Brittany (senior biology major), interpreted the different lengths of the pairs of chromosomes as being related to a mutation. "My first thought was that there was like a weird mutation at first on the top part, but then it could have just been like a smaller chromosome or like chromatid or something and they just combined the small." The lengths of the chromosomes also confused Donna, who said: "I'm more confused

what the small one and what the tall one is? Like why-- like, is this one chromosome I'm looking at? I don't know. I guess I'm confused of is this how many chromosomes am I looking at this one? Is this two? Is this the same chromosome?"

Participants also produced unexpected interpretations of the labeled alleles. Jimmy interpreted the two lines for each homologous pair as the "two strands, like the double stranded DNA for each chromatid," and related the capital and lowercase letters from the heterozygous pair of chromosomes as "the uppercase is for the leading strand and the lowercase is for the lagging strand." The allele "q" was confusing for participants like Donna, who said: "I know there's a q arm. So I'm going to assume that's what the two Qs are. And then I thought it was q and p, but I guess not."

How are undergraduate students using visual literacy skills to reason about the division of chromosomes during meiosis?

Three-quarters of participants (26 of 35) selected the correct answer to the GCA multiple choice question; however, we found that most participants selected the correct answer for the wrong reasons (Table 3). Only 23% of participants (8 of 35) answered the concept assessment question by correctly representing the division of chromosomes during meiosis in their sketches and associated verbal descriptions.

We were surprised to see that 37% of participants (13 of 35) justified their answer using a Punnett square. Although Punnett squares were the most common way for participants to approach this concept assessment question, there was a wide range in how participants were misunderstanding the symbols and misapplying the logic of Punnett squares (Figure 6). Despite their misapplied logic, 11 of the 13 participants who drew a Punnett square selected the correct

answer to the GCA item. Participants like Peggy (junior biomedical science major), Leland (junior biology major), and Piper (senior biology secondary education major) recognized that a two-by-two matrix could generate the four different allele combinations present in the correct answer but failed to realize that Punnett squares are not used to identify combinations of alleles from a single parent. Piper initially had inklings that Punnett squares were associated with a single allele, reflected in her drawings of two separate matrixes for the F and Q genes, but rationalized her final answer with a take on a Punnett square that combined both the F and Q genes. Participants who misapplied Punnett squares tended to demonstrate other unconventional ideas, such as Peggy's conflation of genotype and phenotype, Leland's inconsistent ordering of alleles inside the matrix, and Piper's use of the term "monohybrid" to describe a Punnett square for a meiotic event rather than a cross.

We also saw participants who drew Punnett squares arrive at the incorrect answer to the concept assessment (Figure 6). The participant G (sophomore biotechnology major) drew the structure for two Punnett squares, one which shows F and Q alleles on separate axes (pictured on the left) and one which has a combination of F and Q alleles on each axis (pictured on the right). G then selected the answer "D" which indicated the possible sperm genotypes included Ff, Qq, FQ, fq, Fq, and fQ, and provided the rationale that "I think that's the closest to what I got" based on their completed Punnett square. The rationale of the "closest to what I got" is interesting here, as the Punnett square only provides four combinations of alleles while the answer G selected contains six possible combinations.

In addition to puzzling uses of Punnett squares, we saw participants arriving at the correct answer for other unexpected reasons (Figure 7). In many of these instances, participants tended to answer the GCA item based on their initial (often incorrect) conceptions of chromosomes even

though the text from the assessment item states “two pairs of chromosomes.” Heather drew the dividing cell with X-shapes consisting of both homologous chromosomes. Each X-shaped structure in Heather’s drawing contains both the dominant and recessive alleles. Heather completes meiosis without replicating the chromosomes and with only one cell division. This may be related to Heather’s initial interpretation of the GCA image where she stated “in terms of chromosomes that have already been replicated, there’s two.” Ristan produced a similar drawing of the crossed homologous chromosomes. If we return to his initial interpretation of the concept assessment image, Ristan said “I'm assuming that later, we're going to get to the point where the chromosomes start connecting, and we get into sort of these X shapes. So this figure kind of lends itself to that as well, because you can imagine those two sort of coming together, forming that X.” Ristan’s drawing here reflects his initial idea of the “connecting” chromosomes.

We saw more unique interpretations of connecting chromosomes in Annie and Christin’s drawings (Figure 7). Both chose the correct answer to the GCA item but their drawings of non-homologous chromosomes connected and combined reveals key misunderstandings of meiosis. Annie only includes two chromosomes in her sketch, and the Q and F genes (initially on separate chromosomes) are now depicted on the same chromosome. Annie also uses the telling phrase “when these replicate,” indicating that she is interpreting crossing over of alleles occurring during the replication process. We see a similar misunderstanding of crossing over in Christin’s sketch in which two non-homologous chromosomes are connected at the centromere to represent the process by which chromosomes “cross over.”

When we mapped participants’ drawing of their GCA answer onto the DNA Landscape, we found that most participants (66%, n =23) had unconventional elements of abstraction in their sketches. The unconventional abstraction was most notable in the misapplication of the symbols

in Punnett squares (Figure 6), and we also coded it in the unexpected combinations of chromosomes and genes as well as for the misrepresentation of homologous chromosomes as sister chromatids (Figure 7).

DISCUSSION

Probing visual literacy skills uncovers misunderstanding of chromosome structure and function

Chromosome structure and function is foundational knowledge in biology and is necessary to understand the *Vision and Change* core concept of Information Flow, Exchange, and Storage (American Association for the Advancement of Science, 2011). Despite the importance of this topic in genetics, our findings here suggest that chromosomes continue to be confusing post-secondary students. This confusion was often not evident until we probed participants to engage their visual literacy skills. Similar to previous research (Newman et al., 2012), we found that the majority of participants could correctly provide definitions and answer a multiple-choice concept assessment question about chromosomes; however, when we asked the participants to create and describe sketches of chromosomes, we saw that nearly all of them (97%) had conceptual errors related to chromosome structure or function. This finding illustrates a mismatch between students' declarative knowledge and their mental models of chromosomes.

By asking our participants to draw and describe chromosomes, we revealed new insights into student thinking. For instance, while the majority of participants drew dimensional X-shaped structures that would be considered a "standard representation" of chromosomes (Kindfield, 1994b), descriptions of the X-shape were far less standard. For example, we found a number of participants thought that each chromosome was made of multiple "chunks" or "strands" of DNA

or thought of chromosomes like vessels that were “filled” with DNA. The misconception that chromosomes contain multiple molecules of DNA has been previously documented (Kindfield, 1991) and was even the subject of an item on the Introductory Cell and Molecular Biology Concept Assessment (Shi et al., 2010), but exactly how participants conceptualized the “chunks” of DNA is a new finding. We were surprised to see participants describing chromosomes as containing “four parts” and representing chromosomes as two separate “clusters” of DNA separated by the centromere. Our work here provides further support that students are often confused by the composition of chromosomes and may struggle to understand the nature of the relationship between DNA and chromosomes (Saka et al., 2006). To clarify chromosome structure for students, we recommend that instructors verbally and pictorially explain that each unreplicated chromosome is a single continuous strand of DNA.

While most students drew conventional representations of chromosomes, we uncovered unexpected mental models in several non-standard representations of chromosomes. Some participants drew unconventional side-by-side structures to represent a chromosome, and their verbal descriptions of their sketch revealed misinformed mental models related to the structure and function of the centromere. These misunderstandings may be associated with how centromeres are typically depicted in traditional chromosome models that emphasize processes like cell division (M. U. Smith & Kindfield, 1999). When the centromere is not the specific focus of the model, there may be simplifications to the representation of the centromere that cement student misunderstandings about what the centromere is and does in a chromosome. We suggest incorporating a variety of visual representations of chromosomes with centromeres into biology teaching and being intentional about describing the centromere as a specific segment of DNA

within the chromosome to avoid reinforcing the misconception of the centromere as a separate structure.

We also cast light on what students imagine chromosomes look like by asking them to interpret an image from the GCA. Again, we found mismatches between participants' declarative knowledge about chromosomes and their mental models. This was most evident in the participants who made correct statements, such as that sister chromatids are supposed to be "paired together" in replicated chromosomes, but failed to recognize that the chromosomes in the GCA image were unreplicated and did not actually contain sister chromatids. We have previously documented this confusion of homologous chromosomes for sister chromatids (Wright & Newman, 2011) and our finding here bolsters existing evidence that the distinction between chromatids and chromosomes remains a persistent point of conceptual difficulty for students (Clark & Mathis, 2000; Dikmenli, 2010; Kindfield, 1994c). One way to address some of this confusion is to incorporate active learning opportunities in which students engage with physical, hand-held models that will visually help them identify and distinguish between sister chromatids and homologous chromosomes (Newman & Wright, 2017; M. U. Smith & Kindfield, 1999; Wright et al., 2021; Wright & Newman, 2011).

We further probed participants' conceptualizations of chromosomes when we asked them to create a visual representation of their answer to the GCA item, and here we also observed misalignment between what participants say about chromosomes and what they drew. We saw participants combining homologous chromosomes into single structure and representing a single replicated chromosome containing a heterozygous set of alleles (see the chromosomes that contain both "F" and "f" in Figure 7). Previous research has shown that students produced similar representations of "two-DNA-molecule chromosome" to represent the process of

fertilization (Kindfield, 1991). In the previous study, students joined two haploid gametes, each containing a chromosome with the allele “A” or “a,” into a single X-shaped chromosome with both “A” and “a” alleles upon fertilization, but we were surprised to see participants in our study using this “two-DNA-molecule chromosome” representation *at the start of meiosis*. We were also surprised by students who merged non-homologous chromosomes into a single chromosome structure. We originally presented participants with two sets of non-homologous chromosomes (denoted with alleles F/f and Q/q), but we saw multiple participants drawing structures that contained both F and Q alleles on the same structure (Figure 7). Interestingly, we provided participants with a representation of chromosomes in a single straight line, but participants that combined homologous chromosomes adopted representations with bowling-pin shapes or curved lines that were not present in the GCA image. It is possible that the students who did not adopt the conventions of the straight-line model of chromosomes from the GCA image did not fully understand what the straight lines represented, highlighting the importance of explicitly explaining the conventions of chromosome representations when using them as a visual aid when teaching.

When participants did not use chromosome representations in their drawing of their answer to the GCA item, they often justified their answer with a drawing of a distorted Punnett square. It is never correct to use a Punnett square to represent the process of meiosis, yet almost every student who drew a Punnett square selected the correct answer to a concept assessment question about meiosis. Participants created a variety of corrupted Punnett squares which reveals that students may associate Punnett squares with alleles but may not fully understand that Punnett squares are not appropriate for representing gamete production during meiosis. Our finding provides a chain of evidence that students are misapplying Punnett squares in many

different genetics contexts (Newman et al., 2021; Shaw et al., 2008; Stewart, 1983; Strand & Boes, 2019).

The majority of participants who drew Punnett squares, as well as those who drew "two-DNA-molecule" chromosomes or combined homologous chromosome structures, selected the correct answer to the GCA item for the wrong reasons. By engaging participants' visual literacy skills and asking them to create a visual representation of their explanations, we uncovered that the majority of participants had incomplete or incorrect mental models of chromosomes or meiosis and were getting the item right for the wrong reasons. Had we relied on the multiple-choice answer alone, we would have vastly overestimated our participants' true understanding of chromosome structure and function. Our finding here emphasizes both the limitations of traditional multiple-choice assessments in which students can select the right answer for the wrong reasons (Cerchiara et al., 2019; Fisher et al., 2011; Fulmer et al., 2015; Haudek et al., 2012) as well as the importance of assessing students' visual literacy skills as a robust method of gauging conceptual understanding (Arneson & Offerdahl, 2023; Offerdahl et al., 2017; Schönborn & Anderson, 2006).

Incorporating visual literacy into instruction

During our interviews, many participants justified their drawings or interpretations of chromosomes by referring to what they had seen in textbooks or in their biology classes. Given the number of conceptual errors that we encountered during our interviews, we suggest that there is room to improve how students engage with representations of chromosomes in their textbooks and classes. Traditionally, students are likely to have seen prepared graphics in their textbooks and in PowerPoint slides, and this way of presenting graphics and images reinforces an

intrinsically passive method of learning via images (Higley et al., 2024; Rotbain et al., 2005; Wright et al., 2022). We encourage biology instructors to adopt a more active approach to using representations in their courses. Teaching using visual representations should go beyond putting an image up on a slide or labeling visual structures. While labeling visual representations may help students memorize structures such as components of a nucleotide in a chemical structure (Rotbain et al., 2005), using visual representations to memorize facts about science is not an end goal. Rather, the *Vision and Change* core competency of "Ability to Communicate and Collaborate with Other Disciplines," suggests an end goal of science education is for students to be able to engage with visual representations and build conceptual models that help them participate in the *processes of science* (American Association for the Advancement of Science, 2011; Clemmons et al., 2020).

Incorporating visual literacy into instruction does not need to take much class time. We encourage instructors to take a few seconds to verbally explain the diagrams, figures, and visuals they use in class. When drawing an X-shaped chromosome, instructors can quickly tell students that the "X" represents a replicated chromosome and circle the two sister chromatids represented within that shape. When drawing a centromere using a circle, instructors can mention that even though they made a separate drawing stroke to create the centromere, it is still part of the same single DNA molecule in that condensed chromosome structure.

While interpreting pre-fabricated visual representations is an important part of biology education, we also encourage both instructors and students to be engaged in creating visual representations during class time. Historically, students are rarely asked to sketch in their science classes (Ainsworth et al., 2011; Van Meter & Garner, 2005), but there is tremendous educational value in drawing. Drawing is an important process for biological literacy that is associated with

understanding representations, developing scientific reasoning, and effectively communicating science (Ainsworth et al., 2011). While some instructors and students may feel like drawing requires a strong artistic talent, we emphasize that sketches do not necessarily need to be of the highest artistic quality to be meaningful representations in biology. In fact, quickly-constructed "bad" drawings that require interpretation can increase student interaction with the representation and help to reinforce that quick sketches are useful and acceptable in biology (Higley et al., 2024).

The DNA Landscape provides a framework for visual literacy in molecular biology

We highlight the DNA Landscape (Wright et al., 2022) as a useful framework for instructors looking to teach visual literacy skills and for researchers investigating visual literacy in the context of molecular biology. We found that student misconceptions of chromosomes most often occurred when they mixed visual representations of chromosomes within and across columns of abstractness and scale. We observed that participants who drew unconventional representations of chromosomes that mixed the abstract X-shaped with the more realistic string representations (Figures 4 and 5) tended to have incorrect ideas about chromosome structure and function, often confusing how more experienced biologists traditionally use the string representation. We also saw that students who mixed across the gene and chromosome columns of the DNA Landscape held incorrect ideas about chromosomes. Participants who drew a Punnett square (an abstract representation of genes in the DNA Landscape) to answer the GCA item (which included an abstract representation of chromosomes in the item stimulus) demonstrated misunderstandings of chromosome function during meiosis (Figure 6). We highlight these examples as ways that mixing representations within and across columns of the

DNA Landscape can provide insights into where students may struggle with concepts in molecular biology.

We suggest that instructors use the DNA Landscape to inform their choices related to *what* and *how* they are visually representing molecular biology concepts. For example, instructors teaching about chromosomes should attend to showing representations within the same column, making sure to explain that chromosomes can be represented using abstract lines, as maps or ideograms, or more realistically as strings. In addition to showing students multiple representations within a column of the DNA Landscape, we encourage instructors to incorporate small group discussion and ask students discuss with each other why biologists might use one representation over another. We also suggest instructors take a moment of class time to ask students to reason across the columns of the DNA Landscape to help illuminate the relationships between nucleotides, genes, and chromosomes. Instructors can ask students to consider why it is inappropriate to use a Punnett square to answer a question about meiosis or to think about the relationship between the double helix and chromosome structures. Instructors might ask students if the helix "fills" the chromosome, as some of our participants here have suggested. By giving students to grapple with multiple representations across scale and abstraction in the DNA Landscape, instructors can help their students develop fluency in visual literacy that are necessary for deep understanding of the foundational concepts in molecular biology.

Biology education researchers can use the DNA Landscape as a framework for designing research studies and assessment tasks. Researchers may design future work to study how biology students are thinking about the similarities and differences between representations within columns of the DNA Landscape. There are also opportunities for future work to study how students are conceptualizing scalar relationships across the columns of the DNA Landscape.

When developing research studies or assessment tasks related to visual literacy in molecular biology, we suggest researchers consider incorporating representations across the DNA Landscape.

Future directions

We found that misunderstandings of chromosome structure and function are "sticky," often persisting in students who have already entered advanced undergraduate coursework in their third and fourth year of college. Our findings highlight areas for future research to investigate where students may have derived some of their incorrect ideas and misconceptions about chromosomes. We anticipate that some of these misunderstandings we observed may be related to the colloquial ways that students see chromosomes discussed and represented in K-12 life science curricular materials (Cho et al., 1985). We highlight the use of the word "half" to describe chromatids as one example of this imprecise language that we suspect created confusion in students' understanding of chromosomes. Multiple students referred to sister chromatids (or, in a few cases, a pair of unreplicated homologous chromosomes) as being two "halves" of a replicated chromosome. While our participants frequently used the word "half," and the term "half" appears in open education resources about genetics geared towards a K-12 audience (National Human Genome Research Institute, 2024), this term was never used to describe chromatids in undergraduate biology textbooks (Brooker, 2011; Freeman et al., 2017; Lodish, 2008; Morris et al., 2022; Solomon et al., 2015; Urry et al., 2016). Learning theory suggests that schemas are established based on initial learning and these schemas can be difficult to change (Piaget, 1952), thus the incomplete ideas about chromosomes that are assimilated during middle and high school can persist even when more correct information is presented in undergraduate

courses. As the first learning about chromosomes can shape what is understood (or misunderstood) in future learning, we recommend further investigation into the representations of chromosomes in K-12 contexts.

Limitations

We necessarily focus our results on the errors in student conceptualizations of chromosomes, as these errors provide novel insights into student thinking that may be useful for informing instruction and further education research on conceptual understanding in molecular biology.

We recruited participants from two institutions. It is possible that biology instructors at other institutions may emphasize different aspects when teaching about chromosomes, and as such, we do not make claims that the misunderstandings we observed in our sample population are representative of what misunderstandings might be present in other student populations.

CONCLUSION

Understanding chromosomes is necessary for understanding more complex concepts in genetics. Even though the notion of chromosomes begins as early as middle school, it remains a difficult concept for many undergraduate biology students, which may be tied to their incomplete or incorrect mental models of chromosome structure and function. These difficulties may not be evident in students' verbal descriptions of chromosomes and are only revealed when probing students' visual literacy skills. Asking students to create drawings and interpret visual representations provides key insights into students' conceptualizations of chromosomes. We encourage biology instructors to incorporate opportunities to develop students' visual literacy

skills in molecular biology by using multiple representations of chromosomes at different levels of abstraction, engaging students in sketching representations during class, and asking students to evaluate conventions used in visual representations.

Acknowledgements

Funding provided by NSF DGE 2222337. We thank Christian Cammarota, Meredith Michetti, Shreya Sujith, Aneesh Nallani and Jupiter Chen for help validating the codebook, and we are grateful to the research participants for sharing their ideas with us.

References

Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. *Science*, *333*(6046), 1096–1097. https://doi.org/10.1126/science.1204153

American Association for the Advancement of Science. (2011). *Vision and Change in Undergraduate Biology Education: A Call to Action*. AAAS. https://live-visionandchange.pantheonsite.io/wp-content/uploads/2011/03/Revised-Vision-and-Change-Final-Report.pdf

Anderson, L. W., Krathwohl, D. R., & Bloom, B. S. (2001). *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives.* Longman.

Arneson, J. B., & Offerdahl, E. G. (2018). Visual Literacy in Bloom: Using Bloom's Taxonomy to support visual learning skills. *CBE—Life Sciences Education*, *17*(1), ar7. https://doi.org/10.1187/cbe.17-08-0178

Arneson, J. B., & Offerdahl, E. G. (2023). Assessing the load: Effects of visual representation and task features on exam performance in undergraduate molecular life sciences. *Research in Science Education*, *53*(2), 319–335. https://doi.org/10.1007/s11165-022-10057-7

Bloom, B. S., Krathwohl, D. R., & Masia, B. B. (1956). *Taxonomy of Educational Objectives: The Classification of Educational Goals*. McKay.

Brooker, R. J. (Ed.). (2011). *Biology* (2nd ed). McGraw-Hill.

Brownell, S. E., Freeman, S., Wenderoth, M. P., & Crowe, A. J. (2014). BioCore Guide: A tool for interpreting the core concepts of Vision and Change for biology majors. *CBE—Life Sciences Education*, *13*(2), Article 2. https://doi.org/10.1187/cbe.13-12-0233

Cerchiara, J. A., Kim, K. J., Meir, E., Wenderoth, M. P., & Doherty, J. H. (2019). A new assessment to monitor student performance in introductory neurophysiology: Electrochemical Gradients Assessment Device. *Advances in Physiology Education*, *43*(2), 211–220. https://doi.org/10.1152/advan.00209.2018

Cho, H.-H., Kahle, J. B., & Nordland, F. H. (1985). An investigation of high school biology textbooks as sources of misconceptions and difficulties in genetics and some suggestions for teaching genetics. *Science Education*, *69*(5), 707–719. https://doi.org/10.1002/sce.3730690512

Clark, D. C., & Mathis, P. M. (2000). Modeling mitosis & meiosis: A problem-solving activity. *The American Biology Teacher*, *62*(3), 204–206. https://doi.org/10.2307/4450874

Clemmons, A. W., Timbrook, J., Herron, J. C., & Crowe, A. J. (2020). BioSkills Guide: Development and national validation of a tool for interpreting the Vision and Change core competencies. *CBE—Life Sciences Education*, *19*(4), Article 4. https://doi.org/10.1187/cbe.19-11-0259

Dikmenli, M. (2010). Misconceptions of cell division held by student teachers in biology: A drawing analysis. *Scientific Research and Essay*, *5*(2), 235–247. https://doi.org/10.5897/SRE.9000654

Etobro, A. B., & Banjoko, S. O. (2017). Misconceptions of genetics concepts among pre-service teachers. *Global Journal of Educational Research*, *16*(2), 121. https://doi.org/10.4314/gjedr.v16i2.6

Fisher, K. M., Williams, K. S., & Lineback, J. E. (2011). Osmosis and Diffusion Conceptual Assessment. *CBE—Life Sciences Education*, *10*(4), 418–429. https://doi.org/10.1187/cbe.11-04-0038

Freeman, S., Quillin, K., Allison, L. A., Black, M., Podgorski, G., Taylor, E., & Carmichael, J. (2017). *Biological Science* (Sixth edition). Pearson.

Fulmer, G. W., Chu, H.-E., Treagust, D. F., & Neumann, K. (2015). Is it harder to know or to reason? Analyzing two-tier science assessment items using the Rasch measurement model. *Asia-Pacific Science Education*, *1*(1), 1–16. https://doi.org/10.1186/s41029-015-0005-x

Haudek, K. C., Prevost, L. B., Moscarella, R. A., Merrill, J., & Urban-Lurain, M. (2012). What are they thinking? Automated analysis of student writing about acid–base chemistry in introductory biology. *CBE—Life Sciences Education*, *11*(3), 283–293. https://doi.org/10.1187/cbe.11-08-0084

Higley, L. G., Higley, P. M., & Brosius, T. (2024). The value of "bad" drawing in teaching. *The American Biology Teacher*, *86*(3), 136–142. https://doi.org/10.1525/abt.2024.86.3.136

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, *7*, 75–83. https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

Kalas, P., O'Neill, A., Pollock, C., & Birol, G. (2013). Development of a meiosis concept inventory. *CBE—Life Sciences Education*, *12*(4), Article 4. https://doi.org/10.1187/cbe.12-10-0174

Kindfield, A. C. H. (1991). Confusing chromosome number and structure: A common student error. *Journal of Biological Education*, *25*(3), 193–200. https://doi.org/10.1080/00219266.1991.9655206

Kindfield, A. C. H. (1994a). Assessing understanding of biological processes: Elucidating students' models of meiosis. *The American Biology Teacher*, *56*(6), 367–371. https://doi.org/10.2307/4449854

Kindfield, A. C. H. (1994b). Biology diagrams: Tools to think with. *Journal of the Learning Sciences*, *3*(1), 1–36. https://doi.org/10.1207/s15327809jls0301_1

Kindfield, A. C. H. (1994c). Understanding a basic biological process: Expert and novice models of meiosis. *Science Education*, *78*(3), 255–283. https://doi.org/10.1002/sce.3730780308

Lodish, H. F. (Ed.). (2008). *Molecular Cell Biology* (6th ed). W.H. Freeman.

McHugh, M. L. (2012). Interrater reliability: The kappa statistic. *Biochemia Medica*, *22*(3), Article 3. https://doi.org/10.11613/BM.2012.031

Monrad, S. U., Zaidi, N. L. B., Grob, K. L., Kurtz, J. B., Tai, A. W., Hortsch, M., Gruppen, L. D., & Santen, S. A. (2021). What faculty write versus what students see? Perspectives on multiple-choice questions using Bloom's Taxonomy. *Medical Teacher*, *43*(5), Article 5. https://doi.org/10.1080/0142159X.2021.1879376

Morris, J., Hartl, D., Knoll, A., Lue, R., Michael, M., Berry, A., Biewener, A., Farrell, B., Holbrook, N. M., Liu, J., Heitz, J., Hens, M., Lozovsky, E., Merrill, J., Phillis, R., & Pires, D. (2022). *Biology: How Life Works* (Fourth). W. H. Freeman.

National Human Genome Research Institute. (2024, June 25). *Chromatid*. National Human Genome Research Institute. https://www.genome.gov/genetics-glossary/Chromatid

Newman, D. L., Catavero, C. M., & Wright, L. K. (2012). Students fail to transfer knowledge of chromosome structure to topics pertaining to cell division. *CBE—Life Sciences Education*, *11*(4), 425–436. https://doi.org/10.1187/cbe.12-01-0003

Newman, D. L., Coakley, A., Link, A., Mills, K., & Wright, L. K. (2021). Punnett squares or protein production? The expert-novice divide for conceptions of genes and gene expression. *CBE— Life Sciences Education*, *20*(4), ar53:1-10. https://doi.org/10.1187/cbe.21-01-0004

Newman, D. L., Spector, H., Neuenschwander, A., Miller, A. J., Trumpore, L., & Wright, L. K. (2023). Visual Literacy of Molecular Biology Revealed through a Card-Sorting Task. *Journal of Microbiology & Biology Education*, *0*(0), e00198-22. https://doi.org/10.1128/jmbe.00198-22

Newman, D. L., & Wright, L. K. (2017). Meiosis: A play in three acts, starring DNA sequence. *CourseSource, https://doi.org/10.24918/cs.2017.9*.

Offerdahl, E. G., Arneson, J. B., & Byrne, N. (2017). Lighten the load: Scaffolding visual literacy in biochemistry and molecular biology. *CBE – Life Sciences Education*, *16*(1), es1. https://doi.org/10.1187/cbe.16-06-0193

Piaget, J. (1952). *The Origins of Intelligence in Children* (M. Cook, Trans.; p. 419). W W Norton & Co. https://doi.org/10.1037/11494-000

Rotbain, Y., Marbach-Ad, G., & Stavy, R. (2005). Understanding molecular genetics through a drawing-based activity. *Journal of Biological Education*, *39*(4), 174–178. https://doi.org/10.1080/00219266.2005.9655992

Saka, A., Cerrah, L., Akdeniz, A. R., & Ayas, A. (2006). A cross-age study of the understanding of three genetic concepts: How do they image the gene, DNA and chromosome? *Journal of Science Education and Technology*, *15*(2), 192–202. https://doi.org/10.1007/s10956-006-9006-6

Saldaña, J. (2013). *The coding manual for qualitative researchers* (2nd ed). SAGE.

Schönborn, K. J., & Anderson, T. R. (2006). The importance of visual literacy in the education of biochemists. *Biochemistry and Molecular Biology Education*, *34*(2), 94–102. https://doi.org/10.1002/bmb.2006.49403402094

Schönborn, K. J., & Anderson, T. R. (2009). A model of factors determining students' ability to interpret external representations in biochemistry. *International Journal of Science Education*, *31*(2), 193–232. https://doi.org/10.1080/09500690701670535

Schönborn, K. J., & Anderson, T. R. (2010). Bridging the educational research-teaching practice gap. *Biochemistry and Molecular Biology Education*, *38*(5), 347–354. https://doi.org/10.1002/bmb.20436

Shaw, K. R. M., Van Horne, K., Zhang, H., & Boughman, J. (2008). Essay contest reveals misconceptions of high school students in genetics content. *Genetics*, *178*(3), 1157–1168. https://doi.org/10.1534/genetics.107.084194

Shi, J., Wood, W. B., Martin, J. M., Guild, N. A., Vicens, Q., & Knight, J. K. (2010). A diagnostic assessment for introductory molecular and cell biology. *CBE — Life Sciences Education*, *9*(4), Article 4. https://doi.org/10.1187/cbe.10-04-0055

Smith, M. K., Wood, W. B., & Knight, J. K. (2008). The Genetics Concept Assessment: A new concept inventory for gauging student understanding of genetics. *CBE—Life Sciences Education*, *7*(4), Article 4. https://doi.org/10.1187/cbe.08-08-0045

Smith, M. U., & Kindfield, A. C. H. (1999). Teaching cell division: Basics & recommendations. *The American Biology Teacher*, *61*(5), 366–371. https://doi.org/10.2307/4450699

Solomon, E. P., Martin, C. E., Martin, D. W., & Berg, L. R. (2015). *Biology* (Tenth edition). Cengage Learning.

Stewart, J. (1983). Student problem solving in high school genetics. *Science Education*, *67*(4), 523–540.

Strand, S., & Boes, K. E. (2019). Drawing a link between genetic inheritance and meiosis: A set of exercises for the undergraduate biology classroom. *Journal of Microbiology & Biology Education*, *20*(2), 10.1128/jmbe.v20i2.1733. https://doi.org/10.1128/jmbe.v20i2.1733

Trumbo, J. (1999). Visual literacy and science communication. *Science Communication*, *20*(4), 409–425. https://doi.org/10.1177/1075547099020004004

Urry, L. A., Cain, M. L., Wasserman, S. A., Minorsky, P. V., & Reece, J. B. (Eds.). (2016). *Campbell Biology in Focus* (Second edition). Pearson.

Van Meter, P., & Garner, J. (2005). The promise and practice of learner-generated drawing: Literature review and synthesis. *Educational Psychology Review*, *17*(4), 285–325. https://doi.org/10.1007/s10648-005-8136-3

Wright, L. K., Cortez, P., Franzen, M. A., & Newman, D. L. (2021). Teaching meiosis with the DNA triangle framework: A classroom activity that changes how students think about chromosomes. *Biochemistry and Molecular Biology Education*, *49*(6). https://doi.org/10.1002/bmb.21583

Wright, L. K., & Newman, D. L. (2011). An interactive modeling lesson increases students' understanding of ploidy during meiosis. *Biochemistry and Molecular Biology Education*, *39*(5), 344–351. https://doi.org/10.1002/bmb.20523

Wright, L. K., Wrightstone, E., Trumpore, L., Steele, J., Abid, D. M., & Newman, D. L. (2022). The DNA Landscape: Development and application of a new framework for visual communication about DNA. *CBE—Life Sciences Education*, *21*(3), ar47. https://doi.org/10.1187/cbe.22-01-0007

Figure Legends:

Figure 1. Percent of participants defining chromosomes based on structure, function, or shape. Overlapping regions indicate definitions that met two criteria, with the central overlap indicating a definition met criteria for chromosome structure, function, and shape.

Figure 2. Categorization of participants' initial sketches of chromosomes. Examples of each representation type are reproduced above each bar. From left to right, example sketches were from interviews with the participants Jack, Mia, Donna, Catherine, and Evelyn. Some participants produced several different sketches in response to the interview prompt, so the sum of percentages exceeds 100%.

Figure 3. Initial sketches of chromosomes and the associated verbal description of the sketch. Nadine, Annie, and Andi drew dimensional X-shaped chromosomes. Andi and Pluto drew line X-shaped chromosomes. Alex, Christin, and Mia drew side-by-side chromosomes.

Figure 4. Participant sketches of chromosomes represented using coils and the associated verbal description of each sketch. Jack and Heather drew coiled X-shaped chromosomes. Ristan drew a coiled unreplicated chromosome.

Figure5. Participant sketches of coiled chromosomes generated during follow-up questioning. Participants' initial sketches are in the first column. The second column shows the follow-up sketches. Note that in Teresa's follow-up sketch, she modified her original drawing.

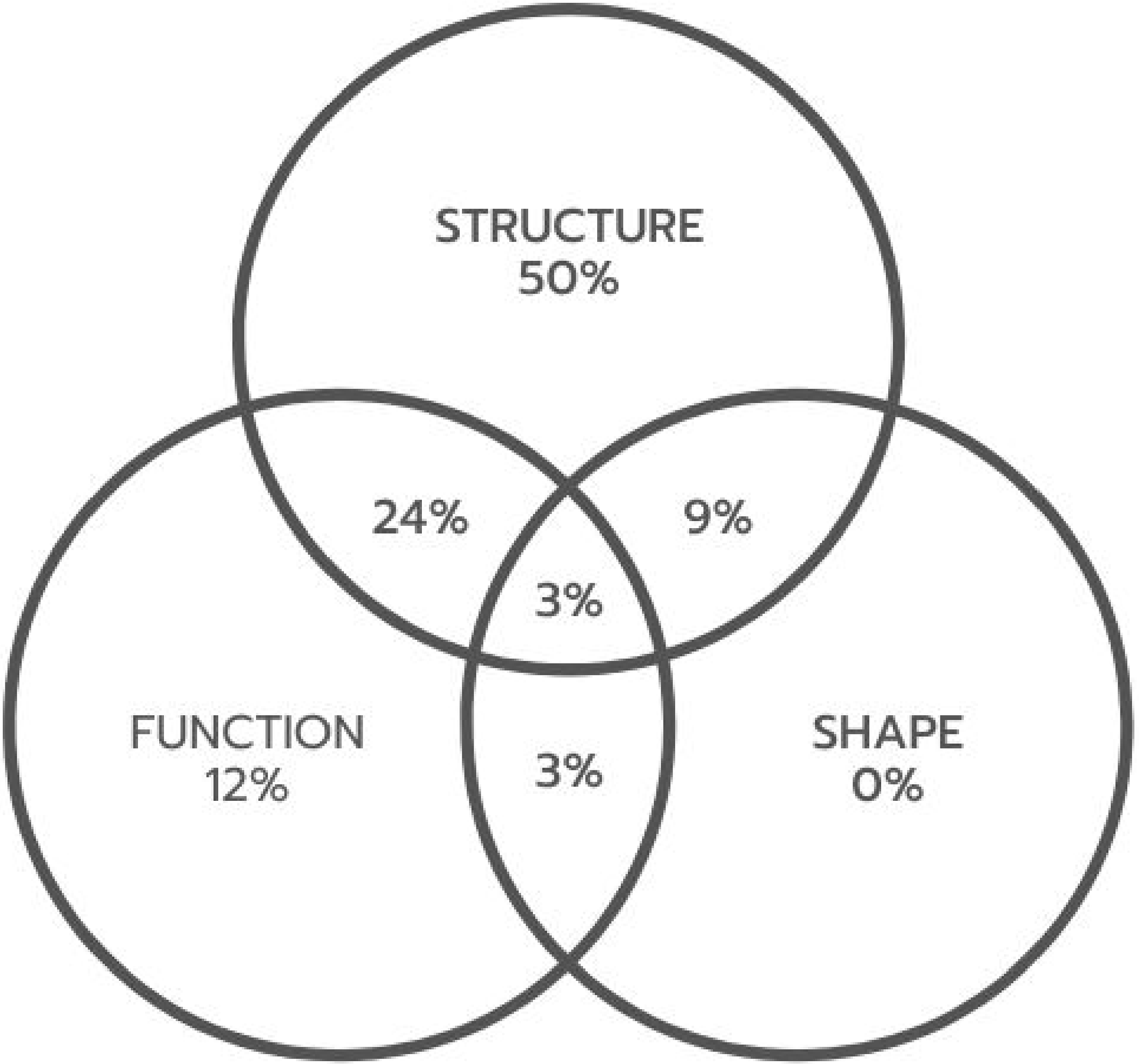
Figure 6. Participant sketches of Punnett squares and associated reasoning to explain their answer to the GCA item. Participants Peggy, Leland, and Piper selected the correct answer to the GCA item. Participant G selected the incorrect answer to the GCA item.

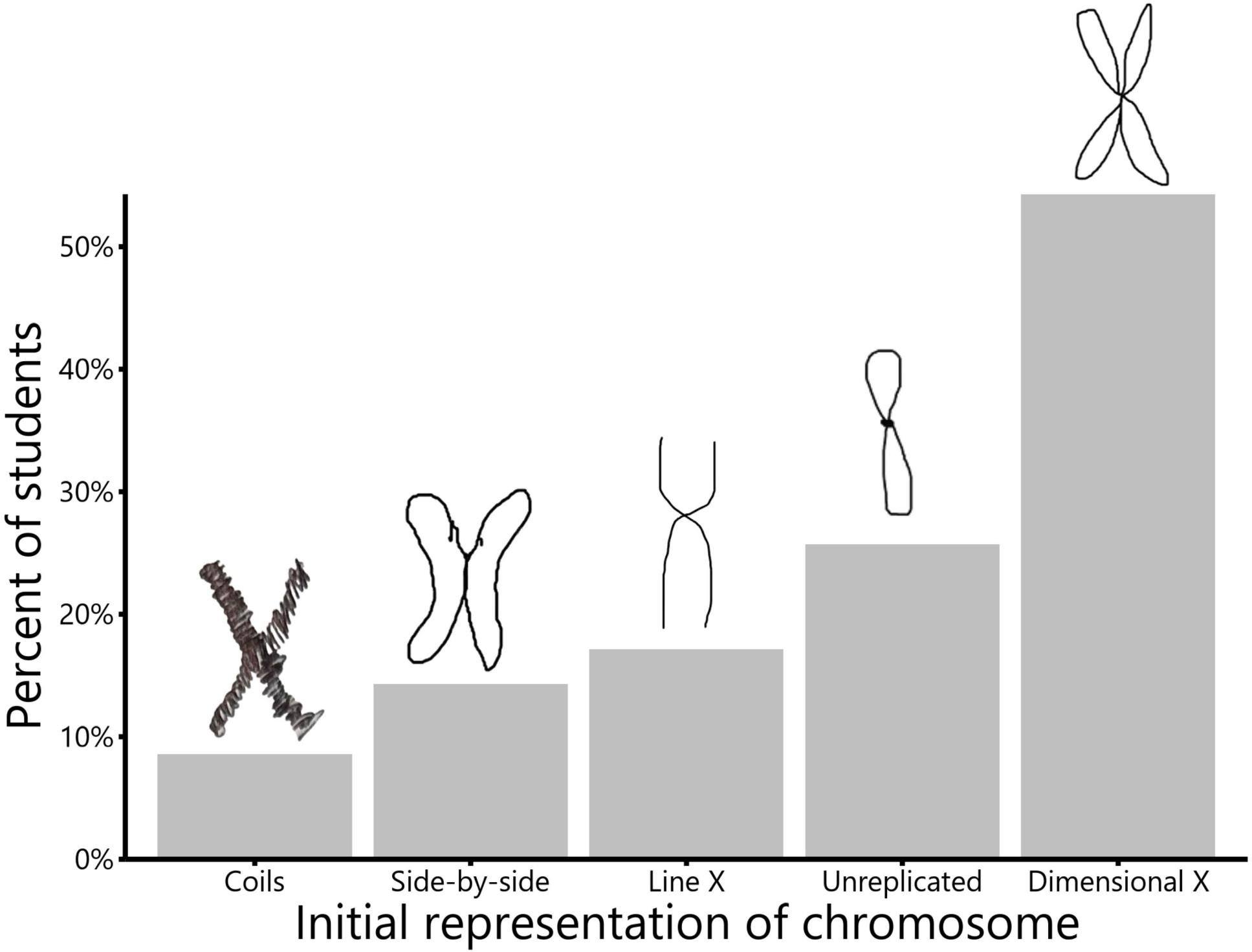
Figure 7. Participant sketches of their answer to the GCA item and associated reasoning to explain their answer. Participants Heather, Ristan, Annie, and Christin selected the correct answer to the GCA item**.**

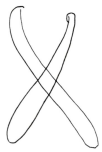
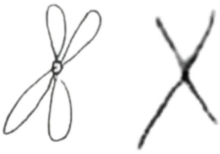
Table 1. Research participant demographics		
	n	%
Institution		
Primarily undergraduate institution	12	34
R2 research institution	23	66
Gender		
Man	6	17
Woman	26	74
Non-binary or gender queer	3	9
Year in college		
Sophomore	13	37
Junior	11	31
Senior	8	23
Master's or Continuing Education	3	9

Table 2. Interview protocol and alignment of interview prompts to visual literacy frameworks		
Interview Prompt	**C-R-M[a]**	**Bloom's Level(s)[b]**
"What is a chromosome?"	C	Knowledge
"Can you sketch a chromosome?"	C-M	Knowledge
"Why did you draw the chromosome this way?"	C-R-M	Knowledge/ Comprehension
Participant is presented with the image of chromosomes from Genetics Concept Assessment item #2. "Please explain what you think about this representation of chromosomes."	C-M	Comprehension
"What about this image makes this an effective representation of chromosomes?"	C-R-M	Evaluation
"Is there anything surprising or confusing about this representation of chromosomes?"	C-R-M	Evaluation
"How does your sketch of a chromosome compare to this representation? What is similar and what is different between your sketch and this image?"	C-R-M	Analysis
Participant is presented with the text from the GCA item #2. "Please talk through how you answered this question."	C-R-M	Comprehension/ Application
"Can you sketch a representation of the answer you selected?"	C-R-M	Application
Notes [a]Abbreviations: C = Conceptual; R = Reasoning; M = Mode (Schönborn & Anderson, 2009) [b]Bloom's levels classified based on the Visualizing Bloom's Tool		

Table 3. Participant interpretation and responses to an item from the Genetics Concept Assessment			
	Incorrect interpretation of image	Correct interpretation of image	Total
Correct response to item with correct reasoning	3	5	8
Correct response to item with incorrect reasoning	16	2	18
Incorrect response to item	6	3	9
Total	25	10	35

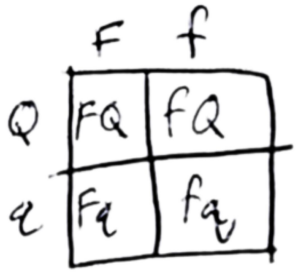
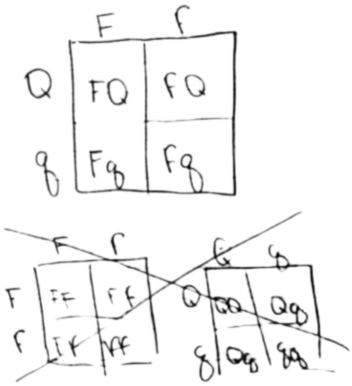
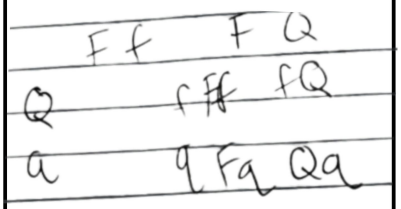

STRUCTURE
50%
24%
9%
3%
FUNCTION
12%
3%
SHAPE
0%

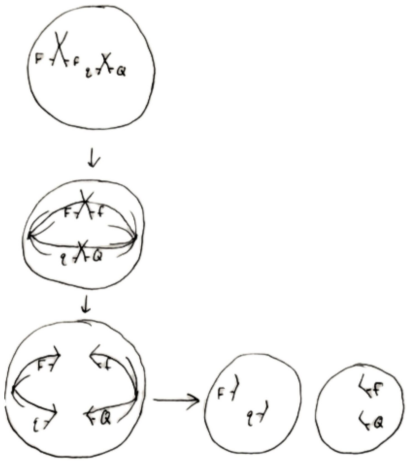
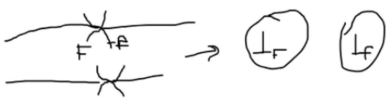
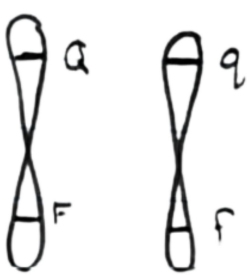

Percent of students
50%
40%
30%
20%
10%
0%
Coils
Side-by-side
Line X
Unreplicated
Dimensional X
Initial representation of chromosome

Sketch of chromosome	Participant's description of sketch
	They just are like two halves that kind of fit together, and I just, that's how I see them in all my biology textbooks, they kind of have two halves together. - Nadine
	Because I know that it has like four parts. Well, your, your code, one section of the code will be on this end and one section will still be on that side. It's double. - Annie
	Why did I draw it [the chromosome on the left] that way? Um, it's simple...it's the simplest way. I mean, okay, really the simplest way to draw a chromosome's like the old school way, but it's when chromosomes are condensed. That's kind of what they look like, if we were to, like, image them [referencing the chromosome on the right]. - Andi
	I mostly drew it like that because like, when you see it in class you see all like the different ones, and the most prominent one is usually one that looks like that 'cause that's like the standard one everyone knows. - Pluto
	I drew it with the sister chromatid with the centromere binding the two pieces together. - Alex
	I know they have two I think they're called chromatids and they're connected in the middle, I think it was called a centromere or something like that. - Christin
	I just drew it like that, because like, that's how I like I saw, like my professors drawing chromosomes and stuff. And like, I think they are explained like, you know, and like in females and males, there's like an X and a Y and or X and an X, you know, and so, something like that, but it could like probably has to do with, I don't know, like, maybe pairs or something. - Mia

Sketch of chromosome	Participant's description of sketch
	I thought of filling it in with like, kind of just zigzag lines to represent that it's like not just the solid shape – it's composed of like strings and coils. - Jack
	I drew it kind of like with like the squiggles instead of just straight lines to represent the condensed chromatin. - Heather
	I think that's to sort of show that it's not like one strand [sketch on the left]...so if I drew this [the single line on the right], I would think 'Oh, this is one strand of DNA that's just bent,' so I'm trying to draw the loops there to show that it is many, many strands of DNA all compressed on top of each other. - Ristan

Initial sketch of chromosome	Follow-up sketches of chromosomes	Participant's description of sketches
		It's usually single when the process starts, and then it becomes an X-shape throughout the process of meiosis... I guess that's just how we've learned it, and DNA is just coiled up, so it's like this [follow-up sketch]. - Norma
		One's just how they are normally [initial sketch on left]. They kind of just exist and the other one's for when it's being replicated into daughter cells [initial sketch on right]...This is like the clusters of the DNA, big clusters [follow-up sketch on top]. Yeah, and this is also another cluster of like DNA [follow-up sketch on bottom]. - Teresa

Sketch of GCA answer	Participant's description of sketch
	And if we're talking about how I got there, I imagined a Punnett Square, because [the item] talks about if [the cell is] undergoing normal cell division, then in theory, there should be equal chance of getting all four types of phenotypes with, there should be two options with a capital F and two options with an uppercase Q and then two with a lowercase of each. And then they should just be matched so that there's no one of the same pair. - Peggy
	I guess the most common way to do [this] is just the Punnett Square. All different. And since it's asking for genotype and not phenotype, this would be all of it. - Leland
	If you're saying that these are just dividing normally, I was going to do a Punnett Square to find all of my variations of the genotypes...So I decided to do them separately, but then I was like, you don't have both. And since it's just to produce sperm, then I was like, 'Oh, well, I can't do that'. And I knew it was monohybrid. So I didn't attempt to do a dihybrid, even though I would never do that by hand. - Piper
	I kind of drew like a [expletive] Punnett Square. I put the capital F, capital Q on one, lowercase on the other side, and I got capital F—heterozygous F, heterozygous Q, and then lowercase f capital Q, capital F lowercase q. So I think that's the closest to what I got.- G

Sketch of GCA answer	Participant's description of sketch
	Yeah, so this is kind of just one example of how it could divide. So I started kind of with how it's represented [in the item]. I kind of mixed the way it's represented on the screen and kind of my representation of more that X. And then the, the, the mitotic spindles-- Well, this, the chromosomes lineup in the center of the cell independently, and then it's the mitotic spindles that come in and pull the pull the sister chromatids apart. And then that splits into two separate cells. - Heather
	There are a host of proteins that will actually pull the combined chromosomes apart, right? So you'll initially look sort of like this. And so if it were to continue, that would be f. And this would be the capital F, which looks very similar, but I promise they're different. That's a little better. So those will be pulled apart. And then in the new daughter cell, it'll only contain the one chromosome with the F. - Ristan
	So it says it's dividing normally to produce the sperm so it would be, I would think it's one allele of one of the half of the chromosome with the other one, or with the other... Okay, so if—when these replicate, this, so this Q [top left] could go with this f [bottom right] and this F [bottom left] can go with that q [top right], but at the same time, yeah, this F [bottom left] could also go with this Q [top left] in this, this f [bottom right] could also go this q [top right], if that makes sense. - Annie
	My first thought would be, I guess that like they cross over. So I guess combining the letters. - Christin