The Cognitive & Educational Implications of Color Use in Drawing to Learn

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The Cognitive & Educational Implications of Color Use in Drawing to Learn

A thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Arts / Science in Neuroscience from William & Mary

by

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Abstract

Drawing to Learn (D2L) is a learning aid that encourages STEM students to interact with abstract concepts in STEM by sketching. D2L is not an intuitive skill, and researchers strive to provide students with guidelines on how to master this method. One potential way to enhance the D2L method for students is by incorporation of visual cues, specifically color. While many students choose to incorporate color into their models without explicit instruction to do so, we have found no research on: a) why students use color in sketching, b) its effects on D2L. This study used interviews, surveys, and course artifacts to identify how and why college students use color in D2L. Our results indicate that students believe color is a useful tool for organizing content and emphasis that thereby improves their recall and understanding. We hypothesize that color may have these effects because of its ability to increase attention and engagement with materials. We found that many students hesitate to use color with D2L on paper because of time constraints and limited access to materials for marking in color, but nearly all students sketching on an electronic device used color. The findings from this study can be used as recommendations for students and instructors and as background for further investigation on the costs and benefits of color in D2L.
Introduction

People innately make use of visual input and mental modeling to understand and interact with their environment. Creating and manipulating mental models employs higher-order cognitive processes that allow us to integrate new information with previous knowledge and form relationships between them (Daur & Long, 2015). The external representation of mental models can thus be applied in academic environments as a learning strategy, especially in STEM (Science, technology, engineering, and mathematics) disciplines. One strategy that is used to externalize mental models in STEM education is Drawing to Learn (D2L)—a visual learning tool that encourages students to create drawings for abstract concepts, facilitating problem-solving and improved synthesis of novel information (Marhalim, 2015; Quillin & Thomas, 2015, Van Meter & Garner, 2005). Benefits arise from the employment of cognitive processes that require the student to deeply organize and engage with learned information (Van Meter & Garner, 2005; Wu & Rau, 2019; Wammes et al, 2016). In addition, D2L requires the student to process information through two sensory stores: verbal and visual. This information can be later encoded and transferred into long-term memory (LTM) in two different ways, visually and verbally, strengthening its memory trace (Meyer, 2009; Wammes et al., 2016).

Though research has supported the benefits of D2L—some of which include enhanced student performance, deeper understanding, and self-efficacy toward course material—strategies to introduce and develop D2L with students remain limited (Quillin & Thomas, 2015; Wu & Rau, 2019). Many researchers in this field have advised students to incorporate visual cues (i.e. spatial cues, and the use of shapes and colors) to decrease cognitive and visual loads (Griffard 2013; Hanna & Remington, 1996; Martinez et al., 2010). However, we have found few studies (e.g. Mayer, 2009) on how specific visual cues—particularly color—affect D2L. The ubiquity
of color in technical illustrations and videos suggests color may be useful in D2L, but I have found neither advice nor data for students relating to instructions for D2L with or without color.

In this study, I will discuss: (i) the literature on the effectiveness of drawing to learn, the cognitive faculties it involves, and how cognition plays a role in the effectiveness of visual learning, (ii) the literature on the significance of color when used as a visual cue in learning, and (iii) my research on use of color by students while using D2L.

Questions asked and answered through my research include

1. What proportion of students choose to use color in D2L (without instruction to do so)?
   - Do the physical means by which students, using paper or e-drawing, sketch affect their propensity to use color?

2. When do students use color in D2L?

3. Why do students use color in D2L?

4. Is there a connection between the vividness of visual imagery and use of color?

5. What are the costs and benefits of color use in D2L?
   - Does one outweigh the other?
**Associative Learning and Memory**

Human memory storage never reaches a maximum capacity (Kolodner, 1983). We are a self-organizing computer program, constantly integrating new with old information and forming new connections—a process known as elaboration (Kolodner, 1983). Though memory is malleable and infinitely expandable, it is not perfect. We encounter problems with learning how to form and maintain *strong* memories in an efficient way. In order to cope with the excess information stored in our brains, we often organize our thoughts into groups, or indices (Kolodner, 1983).

Memory indices—also known as schemas or cognitive structures (CS)—are “how concepts within a domain are organized and interrelated within a person’s mind as the building blocks of meaningful learning and retention of instructional materials” (Ifenthaler et al., 2009). You can think of a memory index as a filing cabinet. Say this cabinet has one drawer, labeled ‘my friends’, and inside lies profiles on all of the friends you have made throughout your lifetime. Now, this cabinet has subgroups: ‘current friends’, ‘childhood friends’, ‘acquaintances’, ‘friends with brown hair’, ‘friends with green eyes’, etc. Some of this information can even overlap: you can have a childhood friend who is also your current friend. You can also have a current friend who you have known since childhood *and* has green eyes. Each individual within those files will contain features/cues that you use to identify that person—these cues are called associations and how they come together forms an association, or semantic, network.

These associations are plastic and are constantly reorganized, fine-tuned, and integrated as we acquire new information (Ifenthaler et al., 2009). For example, associations that you have with one friend may not be unique to them; they may, in fact, trigger the memory of another
friend or event. Say you decide to pull your best friend’s file from this cabinet. Inside is what they look like, where you met, the shoes they always wear, etc. And maybe, the shoes they wear are the same color as a pair of shoes that your sister bought you for your 14th birthday. The association you have with your best friend now branches off into a bunch of new files: who is your sister? What did the shoes look like? What happened on your 14th birthday? This is known as the development of an associative network. In memory networks, bundles of neurons forming one memory trace synapse on others from a related memory trace, forming a connection between the two. According to the search associative memory model (SAM), “items presented for recall acquire a set of mutual associations when stored temporarily in working memory buffers” (Recanatesi et al., 2015). The more connections/associations made during a trace’s transition between working memory buffers and consolidation, the more accessible it is for retrieval. Studies such as Recanatesi et al.’s (2015) have demonstrated that people have a tendency to more accurately and more freely retrieve items with “larger numbers of neurons in their representations” (Recanatesi et al., 2015). How frequently these neurons are activated and how they connect to one another also affects the strength of a memory trace and what details are recalled. The classic Craik and Tulving (1975) experiments discuss how strength and retention of a memory trace depend on a) depth of processing and b) the degree of elaboration during encoding. One of the large takeaways from this study states that “the qualitative nature of the task, the kind of operations carried out on the items, that determines retention” (Craik and Tulving, 1975). Thus, engaging more with materials, especially by linking more cues or codes to a memory trace, may facilitate deeper levels of processing, thereby leading to longer retention (Craik and Tulving, 1975; Schnotz & Horz, 2010; Recanatesi et al, 2015).
Creating these associations is a mechanism that can be used to bypass some constraints of memory retrieval (i.e., inability to retrieve information, inaccurate retrieval, etc.)

While an infinite memory store may sound like a benefit, it also makes it difficult for us to accurately retrieve information from memory. Williams & Hollan (1981) expanded upon three principles of retrieval—partial information, description, and large memory capacity—and how they challenge accurate memory retrieval. Relevant to my research are two of these: partial information and large memory capacity.

Although our brains may never reach a point where they can no longer encode new memories, they are incapable of encoding all elements of a stimulus into memory. Partial information retrieval is defined as encoding only limited amounts of information from our environment for later retrieval (Williams & Hollan, 1981). We tend to select key features or elements for encoding, compacting information for memory storage (Williams & Hollan, 1981; Mayer 2009). Williams & Hollan (1981) used meeting a new person as an example. Say this person is named Jane Smith. Maybe you’ll register a rough image of her face, red hair, and her first name: Jane. Now you have formed an index, or file, just for Jane under “people you just met”. Later that day, a friend asks you what Jane’s last name was but you cannot seem to remember. This is a consequence of partial information encoding or improper indexing—or, the formation of incorrect associations. In the presence of information overload, our brains only select a handful of key elements it believes are most pertinent for us to remember. Partial information retrieval does not only apply to everyday stimuli but especially in learning (Mayer 2009; Quillin & Thomas, 2015). In the presence of too much information, students are typically unsure of how to distinguish between important information and minute details, affecting their understanding of course material—to be expanded upon below. Because humans only encode
for a few things at a time, we tend to compensate for memory gaps by substituting fabricated information—or guesses—in place of the missing bits.

Improper selection of key elements in learning is an obstacle that instructors are constantly trying to tackle while teaching their curriculum: how can material be delivered to students in an effective way that prevents cognitive overload and evades retrieval constraints. One tactic important to this study is the application of associative networking (or associative learning) as a tool for memory and learning. Integrating old and new information is a valuable way to form new connections that strengthen a memory trace, stress important information, and promote retrieval. Learning new information promotes associative learning by engaging multiple cognitive/sensory modalities and motor functions to externalize abstract concepts—forming memories networked with multiple different memory stores, strengthening their traces.
Drawing to Learn (D2L)

Humans often make use of visual input and mental modeling to understand and interact with their environment, explaining why our visual working memory stores have a larger storage capacity than our verbal working memory (Wammes et al., 2016). Instructors can take advantage of this by using visual aids in learning to minimize cognitive overload of processing systems by intertwining verbal and visual information (Mayer, 2005; Keller & Grimm, 2005):

“Information visualizations can reduce extraneous cognitive load by…[using] different presentation codes (e.g. verbal, pictorial, spatial) to distribute the cognitive load on different information processing systems. As a result, the user has more free cognitive capacity for managing the learning task” (Keller & Grimm, 2005).

Due to the complexities and abstract concepts in STEM fields, experts routinely draw to represent internal mental models for communication, deep processing, and problem-solving in STEM fields (Quillin & Thomas, 2015; Van Meter & Garner, 2005; Wu & Rau, 2019; Wammes et al., 2016; Griffard, 2013). Use of D2L allows students to learn and interact with abstract and complex processes, improving clarity (Kindfield, 1994). In biology, for example, without diagrams, it is extremely difficult to visualize phenomena such as intracellular processes or relationships between taxa that are complex or only indirectly observable. Representing complex concepts in drawings externalizes verbal representations for visual analysis and vicarious enactment of a process (in the sense of playing out / manipulation of a learned process
promoting comprehension and knowledge acquisition (Kindfield, 1993; Wammes et al., 2016). Table 1 summarizes benefits of D2L.

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Source(s)</th>
</tr>
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<tbody>
<tr>
<td><strong>Boosts Memory by</strong></td>
<td></td>
</tr>
<tr>
<td>● Facilitating deep levels of information processing (LoP)</td>
<td>● Wu &amp; Rau, 2019</td>
</tr>
<tr>
<td>● Incorporating multiple memory codes into one trace, strengthening memory and efficient recall</td>
<td>● Van Meter &amp; Garner, 2005; Wu &amp; Rau, 2019; Quillin &amp; Thomas, 2015</td>
</tr>
<tr>
<td><strong>Assists in</strong></td>
<td></td>
</tr>
<tr>
<td>● Externalizing visually ambiguous concepts</td>
<td>● Wu &amp; Rau, 2019</td>
</tr>
<tr>
<td>● Problem-solving</td>
<td>● Van Meter &amp; Garner, 2005; Quillin &amp; Thomas, 2015; Wu &amp; Rau, 2019; Dauer &amp; Long, 2015; Kindfield 1993</td>
</tr>
<tr>
<td>● Recall and triggering memories for related information through networking and dual coding</td>
<td>● Van Meter &amp; Garner, 2005; Mayer, 2009; Paivio, 1991</td>
</tr>
<tr>
<td>● Higher level thinking and engagement with material</td>
<td>● Van Meter &amp; Garner, 2005</td>
</tr>
</tbody>
</table>

Table 1: Benefits of D2L according to literature.

Once adopted, D2L is an effective method that boosts encoding/retrieval, observational processes, and overall conceptual understanding via the engagement of multiple cognitive modalities (Van Meter & Garner, 2005; Wammes et al., 2016; Heideman et al., 2017). Multiple authors (Table 2) have identified useful processes required to engage in D2L when presented
with verbal information (including) (Wammes et al., 2016; Heideman et al., 2017; Wu & Rau, 2019):

a) Elaboration

b) Visualization

c) Physical creation /motor coordination

d) vicarious enactment by playing out and manipulating a learned process, and

e) pictorial representation.

Multimodal learning tactics such as these enhance active processing and engagement with materials, which facilitate improved encoding and retrieval, in addition to deep conceptual understanding via the formation of connections between new and old cognitive structures (Schwamborn et al., 2011; Daur & Long; Wu & Rau, 2019).

A framework for engaging with drawings (i.e. how students engage with drawings) has been described by the Cognitive Theory of Multimedia Learning (CTML) (Mayer, 2009). Quillin & Thomas (2015) and others proposed that forming mental models of material that can be externally represented as drawings involves 3 cognitive processes:

a) Selection: the filtration information that will be included/excluded from the model

b) Organization of visual and verbal input, and

c) Integration of elements into a cohesive internal depiction.

These steps apply ways of organizing mental models, as mentioned by Mayer (2009), with ways of organizing drawings when executing D2L.
An alternative approach in a model by Wu & Rau (2019) (Table 2) depicts the sociocultural and cognitive learning processes involved in D2L. In this approach, D2L is a hierarchical skill with mostly cognitive foundations:

![Hierarchy of cognitive and sociocultural processes involved in D2L, adopted from Wu & Rau, 2019.](image)

**Fig. 1:** Hierarchy of cognitive and sociocultural processes involved in D2L, adopted from Wu & Rau, 2019.

While Quillin & Thomas (2015) only specifies the cognitive processes directly involved in translating verbal input into a sketch, Wu & Rau’s 6 Learning Processes specify the cognitive modalities required to create, understand, and study an academic drawing/sketch, and how they hierarchically relate to one another. The 6 Learning Processes also include the sociocultural implications of D2L in field-based communication and mastery. Thus, Quillin & Thomas (2015) and Wu & Rau’s (2019) models are closely interconnected, as one cannot successfully climb each tier without having mastered the skill of generative learning (i.e. selection, organization, and integration of a new schema) (see Table 2).

Unfortunately, D2L is not an intuitive skill (Quillin & Thomas, 2015). Using D2L necessitates visual literacy, high self-efficacy towards drawing, and an understanding of model-based reasoning, all of which require instruction, feedback, and practice (Quillin & Thomas, 2015; Van Meter & Garner, 2005). Most mistakes occur in the Generative Learning phase of Wu
& Rau’s hierarchy. First, students seldom know how to properly “select” key elements for organization when using D2L as a study tool. Often, students select too much or too little information for encoding, and or over-allocate attention to minute details (Mayer, 2009; Quillin & Thomas, 2015). Selecting too much information to incorporate in an academic sketch or over-allocating attention to small details can result in cognitive overload, thus obscuring the most important concepts required for understanding a mechanism, leading to gaps in the learner’s knowledge. Cognitive load also increases when information is improperly organized during internal mental processing of externally represented information (i.e. a sketch). Increased cognitive load makes it harder to accurately retain information and impedes deep processing of class content. Contrarily, leaving out pertinent information (or including too little information) in a sketch can also result in knowledge gaps, limiting a student’s understanding and hence, academic performance (Kindfield, 1993).

Improper selection and organization of information results in incompetent evaluation/understanding (incompetent Generative Learning), minimizing the efficacy of D2L and impeding students from climbing Wu & Rau’s ladder of cognitive and sociocultural learning. Without proper instruction, students will be incapable of thoroughly engaging with and accurately assessing their understanding of new content (Self-Regulation), integrating novel concepts with old mental models (Mental Model Integration).

Research on instructing and advising students on how to make effective use of D2L in (and outside) of the classroom is limited. Chabris & Kosslyn (2005) have suggested that representational correspondence is key to making a good diagram: “to be effective, diagrams should depict information in the same way that our internal mental representations do.” However, suggestions like these have little to do with guiding students on how to properly select,
organize, and integrate new information into pre-existing cognitive structures/indices. To facilitate proper selection, organization, and integration of new information, experts have recommended fusing visual cues (i.e. symbols, color, etc.) into sketches so as to draw more attention to key elements in a sketch and organize visual information. The more organized the information, the easier it is to: a) separate and synthesize the different parts of a sketch, b) accurately encode and retrieve from memory, and c) interconnect the information with other topics from a specific domain (Daur & Long, 2015). Table 2 summarizes cognitive models that relate to D2L.

<table>
<thead>
<tr>
<th>Theory</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive Theory of Multimedia Learning</td>
<td>● Drawing to learn requires the formation of mental models from verbal/textual information (Quillin &amp; Thomas, 2015)</td>
</tr>
<tr>
<td>(CTML)</td>
<td>● Forming mental models engages 3 cognitive processes: CTML (Mayer, 2009)</td>
</tr>
<tr>
<td></td>
<td>a. Selection of relevant information via sensory processing</td>
</tr>
<tr>
<td></td>
<td>b. Organization of visual and verbal input</td>
</tr>
<tr>
<td></td>
<td>c. Integration of elements into a mental model</td>
</tr>
<tr>
<td></td>
<td>● Supports that adding pictures to text enhances recall because “two codes in memory are better than one” (Schnotz &amp; Horz, 2010)</td>
</tr>
</tbody>
</table>
| The 6 Learning Processing in Drawing | ● A hierarchy of four cognitive learning processes and two sociocultural learning processes  

|  | ● The 4 Cognitive Processes (Wu & Rau, 2019)  

|  | a. Generative Learning — the way students engage deeply with content by translating and organizing information  

|  | b. Self Regulation — how students self-assess their understanding through reflection; the way students filter their attention to relevant content  

|  | c. Mental Model Integration— integration of learned content with prior knowledge; adapt mental models to include new information  

|  | ■ Requires Generative Learning and self-regulation  

|  | d. Spatial Cognition— use of visuospatial and bottom-up/top-down processing cues to enhance mental models  

|  | ■ Top-down processing is used to make connections between new and previous knowledge to help make sense of new content  

|  | ■ Bottom-up processing is used to interpret visual cues (i.e. annotations, color, spacing/symbols) to make sense of a drawing  

|  | ● 2 Sociocultural Processes (Wu & Rau, 2019)  

|  | a. Mediated Discourse—use of universal conventions for recurring concepts within a discipline to help students understand and communicate their ideas into a drawing  

|  | b. Disciplinary Practice — drawing to help students solve and interact with problems and practices within their disciplines  

| Dual Code Theory | ● Recall is enhanced by the visual and verbal representation of a learned concept  

|  | ○ “two codes in memory are better than one” (Schnotz & Horz, 2010)  

|  | ● 3 types of processing all or none of which may be employed depending on the task at hand (Paivio, 1991):  

|  | ○ Representational — activation of a verbal or nonverbal model  

|  | ○ Referential— activation of a verbal model by a nonverbal model; vice versa
Table 2: Cognitive theories related to drawing to learn benefits according to literature.

I hypothesize that effectively colored sketches provide beneficial visual cues by one or more of the following:

a) improving engagement with material
b) making the components of a sketch more easily differentiable
c) better highlighting important information

All of these might decrease students’ cognitive and visual loads to facilitate more accurate encoding, understanding, and retrieval. CTML relates to a) through c) as formation of mental models increases engagement with and manipulation of materials by engaging multiple cognitive processes. Additionally, incorporation of color in D2L models may make these cognitive processes easier on the student by easing their ability to select, organize, and integrate the important parts of a sketch. Wu & Rau’s (2019) 6 Learning Processes in Drawing are also linked to a) through c) above, as the extra time required to add color into a sketch may allow students to more thoroughly work their way through the hierarchy of cognitive processes/sociocultural processes involved in D2L. Lastly, Dual Coding Theory applies to a) as linking multiple visual cues using color and form, in addition to the abundant cognitive and motor processes codes associated with D2L may strengthen the trace for improvement of memory and retrieval.

Take the figure below as an example. These two images are from a sample submitted from one of our interview participants who used color in their sketches.
**Fig. 2:** (A) Original student-generated sketch of the biological process including color and (B) a version of (A) that I modified by removing color. In the color version, the student used standard black to represent the structural foundation and either gray or colors for five features. (The biological process shows the role of different proteins involved in vesicle formation within cells during endocytosis. *Participant ID: CAS42)

Image (A) on the left is easier to synthesize as each structural element is grouped by color. The contrasting colors in (A) make it easier to differentiate and group repeated elements together at a glance. Figure (B), on the other hand, initially requires more cognitive effort to decode because all structural elements in the sketch are in a single shade. Therefore, (A) can induce a decreased visual load for its audience, meaning it may be easier to process and comprehend, while orienting attention to specific details in the sketch. The difference may be a consequence of color as a visual element that is parallel processed by the brain in that color requires no conscious cognitive effort for perception, unlike labels/words (Chang et al., 2018). The use of color-coding in this sketch may also create an associative processing effect through the development of cognitive connections between different stimuli/events. In this case, associative processing refers to the connections between a unique color cue and each element in a sketch. Linking each element to its own color might enhance the student’s ability to spend
more time focusing on parts of the sketch that are connected to one another, as opposed to spending cognitive resources on trying to understand relationships and connections.

Prior to elaborating on the benefits of color in visual learning, I believe it is important to illustrate how students use color D2L and externalize mental models compared to textbook figures (Fig. 3).

![Fig. 3: Comparison of a textbook illustration and student-drawn figure on the depiction of synaptic transmission in chemical synapses. (A) Simplified student-drawn sketch. (B) A corresponding complex textbook figure. Participant ID: CAS17.](image)

While the two sketches (Fig. 3-A and Fig. 3-B) do not attempt to show all the same features, the student sketch contains as much as or more information than the textbook figure while using color to group related or repeated elements. The student sketch is likely much easier for the student to process, practice, recall, and apply.
Color, Cognition, & Visual Learning

Visual cues are tools that enhance visual learning (Wu & Rau, 2019; Griffard, 2013). Examples of visual cues in illustrations may include the use of color, emboldened/italicized text, purposefully placed arrows, and spatial cues. The figure below (Fig. 4) is an example of how visual cues can be incorporated into a sketch.

![Figure 4](image_url)

**Fig. 4**: Example of how students use visual causes and color in D2L in a student submitted sample sketch of water leaving the descending loop of Henle.

Figure 4 is an example of student use of visual cues including shape, color, and spatial cues to communicate ideas about a learned process. These cues used in typical student drawings are also
listed in a review by Griffard (2013) discussing how academic illustrations communicate ideas using ubiquitous meaningful cues as part of visual literacy—or the ability to use, interpret, and create meaning from visual cues in an image. Gaining insights into how, when, and why students use color may improve instruction in D2L that can enhance visual literacy in students.

At this time, there are few resources available that guide instructors on how to incorporate visual cuing into mechanisms for visual modeling (i.e. in textbooks, class notes, drawing to learn, etc.) To date, we have found no research on whether visual cues (such as color) would be useful to students who use D2L.

*Why Should Instructors Care About Color?*

Visual stimulation is a powerful tool that “rewires the brain, making stronger connections while fostering visual thinking, problem-solving and creativity” (Marhalim, 2015). The effect of using color as a visual stimulant have been evaluated in multiple studies. The use of color during task performance has been correlated with improvements in attention, motor skills, academic performance, and much more (Gaines & Curry; Imhof, 2004; Zentall & Dwyer, 1989; Kennedy, 2005). Implications for the benefits of color (as a direct and indirect tool) in a learning environment based on literature are described in the chart below (Table 3).

<table>
<thead>
<tr>
<th><strong>Benefits of Color Based on Literature</strong></th>
<th><strong>Description</strong></th>
<th><strong>Sources</strong></th>
<th><strong>Direct / Indirect Tool</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>It is an Unconsciously Processed Visual Cue</td>
<td>Color is a basic element in visual perception, meaning it requires no conscious effort to process</td>
<td>Chen, 2017; Hanna &amp; Remington, 1996; Keller &amp; Grimm, 2005; Martinez et al., 2010; Treisman &amp; Gormican, 1988</td>
<td>N/A</td>
</tr>
<tr>
<td>Reduced Visual Search Time &amp; Cognitive Load</td>
<td>Makes elements of an illustration easily identifiable, reducing visual search time and consequently, cognitive effort spent on finding/tracking elements in a sketch</td>
<td>Chang et al., 2018; Gozli et al., 2015; Keller &amp; Grimm, 2005;</td>
<td>Direct</td>
</tr>
<tr>
<td>Enhance Information Organization</td>
<td>Color can be used as a cue to group similar elements of a sketch together or distinguish them different elements apart from one another</td>
<td>Chang et al., 2018; Hanna &amp; Remington, 1996; Keller &amp; Grimm, 2005; Kumi et al, 2013.</td>
<td>Direct</td>
</tr>
<tr>
<td>Improved Attention</td>
<td>Researchers have demonstrated that incorporation of certain colors in learning environments increase attention to material</td>
<td>Dzulkifli &amp; Mustafar, 2013; Chang et al., 2018; Gaines &amp; Curry, 2011; Imhof, 2004; Kennedy, 2005; Marhalim, 2015; Singg &amp; Mull, 2017; Zentall &amp; Dwyer, 1989</td>
<td>Direct</td>
</tr>
<tr>
<td>Better Affective States Towards Course Material, Memory, and Retrieval</td>
<td>The effect of color on enhancing attention to course material facilitates more accurate encoding and transfer of information into memory stores. Color impacts mood and motivation, meaning that use of color in academic environments can increase learning enjoyment, positively affecting student motivation to learn and study</td>
<td>Dzulkifli &amp; Mustafar, 2013; Chang et al., 2018; Gaines &amp; Curry, 2011; Imhof, 2004; Kennedy, 2005; Marhalim, 2015; Singg &amp; Mull, 2017; Zentall &amp; Dwyer, 1989</td>
<td>Indirect</td>
</tr>
<tr>
<td>---</td>
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<tr>
<td>Facilitate Deeper Information Processing</td>
<td>Color and shape are not bound together in memory, thus binding the two in memory requires active processing. Ascribing color to a sketch also requires allocation of focal attention to these visual features may result in deeper information processing, strengthening a memory trace</td>
<td>Hanna &amp; Remington; Marhalim, 2015</td>
<td>Indirect</td>
</tr>
</tbody>
</table>

**Table 3:** Benefits of use of color according to literature.
Color to Reduce Visual Search Time & Cognitive Load: Color can serve as a direct tool in lessening cognitive and visual loads. Many cognitive researchers in education have pointed out that color is a pre-attentive processing element of perception, meaning it requires no conscious effort to perceive (Chen, 2017; Healy, 2012). Color as a pre-attentive processing cue has been directly correlated with lower visual search times and preservation of cognitive energy. The figure below (Fig. D)—adapted from Healy, 2012—illustrates this perfectly.

![Fig. 5: Find the target circle based on the difference in hue. Figure from Chen 2017.](image)

It does not take any time for the observer to search around the image and find the target (the red circle), the target is easily spotted after merely glancing at the image. Therefore, constraints such as visual search time and cognitive load are nearly eliminated in this task by the inclusion of color in this graphic.
I further adapted the previous figure to compare pre-attentive processing of color versus shape (Fig. 6). Both color and shape are efficient pre-attentive cues for visual processing (Healy, 2012). Looking only at the image on the right, it is easy to distinguish the elements apart based on curvature. Looking only at the image on the left, it is easy to distinguish the different elements apart based on color. In the image on the left (Fig. 6-A), the different elements are rapidly distinguished based on color. In contrast, a process that is slower is the image on the right (Fig. 6-B), distinguishing the elements by shape.

*Color + Visual Organization:* A research article by Kumi et al. (2013) specifies that color “[enables] the identification and organization of information.” Organization of information using color may be accomplished using color-coding, as illustrated by a student sample sketch in Fig. 2.

Because color and form are both useful visual cues for grouping related elements (Healy, 2012), using color and form *together* to symbolize related and unrelated elements may make it easier for the observer to group the many parts of a sketch together, as opposed to only using form (shape) to organize the sketch. Using color-coding to group elements may also improve the
quality of a cognitive structure, decreasing cognitive load which frees up space in visual working memory (VWM) stores for more accurate encoding and deeper processing of new information. This may be because grouping by use of color may facilitate visual chunking representations of an image in working memory or chunking of elements in a visual field (Zhang et al., 2012; Woodman et al. 2003). As mentioned previously, visual working memory has a limited capacity. Visual chunking representations allow individuals to increase their working memory capacity by chunking similar visual elements together according to Gestalt’s principles of bottom-up processing/perception (Zhang et al., 2012; Woodman et al. 2003). Thus, “individuals can create higher order cognitive chunks through assimilation of individual elements according to their properties, and these chunks allow more features to be remembered than with remembering individual elements” (Zhang et al., 2012). A feature which may play a role in this phenomenon is color, which chunks visual elements together on the basis of Gestalt’s principle of similarity (Wallace et al., 1998).

*Color, Memory, (& Attention):* Color is a visual stimulant that can be used to easily capture attention or induces selective attention towards a specific target. During testing and retrieval phases of learning, color coding can be useful for information retrieval (Chang et al, 2018). This can manifest itself in different ways. First, color increases attention to materials “which [helps] such information to be transferred to short-term and long-term memories, thus increasing their chance of memorizing such information” (Chang et al., 2018, citing Dzulkifli & Mustafar, 2013). Second, linking more cues to a cognitive structure stabilizes its memory and makes it easier to recall (Takashima et al, 2007). Ascribing colors meaning for elements in a sketch—especially in a way that parallels social and natural color constructs—may network
these various ideas, increasing the number of cues within a cognitive structure, thus, stabilizing its memory trace. Memory trace stabilization via cueing will make automatic and efficient information retrieval during exam time more likely. This would be an especially helpful tool for recurring concepts in STEM—i.e. common ions (Na+, Ca2+, K+) and common molecules (PO42-, H2O, O2), chemical functional groups (aldehydes, ketones, alcohols, amines,) color conventions for oxygenated and deoxygenated blood, and much more. Third, the world is inherently filled with colorful cues. When looking around a room, the student may stumble upon a colored object that is the same color as a concept in their sketch. Through learned association, this may trigger a memory that initiates the retrieval process for a learned concept. Note that parts of a learned process are frequently intertwined within the same neural network. All it takes is activation of one node to trigger activation of the rest.

*Color, Affect, (& Attention):* Those new to D2L often feel uncomfortable with using D2L as a result of lack of exposure to this learning method (Quillin and Thomans, 2015; Van Meter & Garner, 2005). Poor affect generates anxiety and sadness towards a task, driving the learner to accept defeat with respect to task-dependent failure. Studies by Kumi et al. (2013) and Marhalim (2015) on how color and affect influence learning outcomes supported the inclusion of specific colors in learning materials.

Affective Event Theory (AET) states that human emotion and behavior are influenced by contextual cues existing in our environments (Kumi et al., 2013; Marhalim, 2015). Perception of these cues affect our attitudes based on our past experiences with them that may be positive or negative. If someone has a poor affect towards drawing because they were told they are not a good artist, that person will appraise themselves as a poor artist, and being asked to use D2L in the classroom will provoke a negative response (Kumi et al., 2013; Marhalim, 2015). The student
will negatively appraise the task and convince themselves that they will be unable to succeed in mastering this skill, inducing negative affect and anxiety towards D2L. Increased negative affect has been positively correlated with poorer performance due to decreased avoidance motivation, or the desire to avoid task failure (Kumi et al., 2015; Marhalim, 2015). Decreased avoidance motivation occurs in those with negative affect as a result of negative cognitive appraisal, leading them to believe that failure is imminent (Kumi et al., 2015; Marhalim, 2015). Because color perception has been heavily intertwined with emotional, physiological, behavioral responses, researchers have tested their relationships with affect in learning environments, finding that colors can make tasks more enjoyable, decreasing negative affect. Decreased negative affect also yielded higher retrieval and performance in memory-related tasks, likely due to increased attention (Kumi et al., 2015; Marhalim, 2015). These results give us reason to believe that color may make D2L more enjoyable for those with poor self-efficacy toward visual learning and drawing. Improved self-efficacy in D2L may assist increase attention to course material and boost learners’ confidence, improving their comprehension of the material.

**Color as a Learned Association:** Reactions produced by color-related learned associations indicate that color perception and processing can have strong effects on how we respond to and engage with our surroundings. Where do these associations come from? Our brains are constantly searching for patterns within our surroundings to prime ourselves for what to expect in the real world (Gozli et al., 2015). Part of these common representations of color cues are sometimes derived from naturally and socially occurring color conventions—i.e., green for leaves, blue for skies, red for stop signs, etc. Repetitive exposure to these conventions over time results in strong learned associations that may affect color choices when incorporating color into visual modeling tasks—i.e., use of reds to symbolize emphasis, incorrectness/danger, or
Forming associations between colors and recurring visual elements in D2L may help students make the process of forming and interpreting sketches more predictable over time. As an example, consider a lecture about the relative concentrations of ions in and outside of a human cell. Sodium and Calcium are highly concentrated on the outside of the cell, whereas potassium is highly concentrated inside of the cell. Students can ascribe Na\(^+\) and Ca\(^{2+}\) different shades of the same color or similar colors to represent the fact that they are highly concentrated in the extracellular space, and ascribe K\(^+\) a contrasting color to represent that it is highly concentrated on the inside of the cell. A potential depiction of a D2L model that uses color for this concept is shown in the figure below:

![Fig. 7: Simple sample cell model on how color can be used to distinguish elements in a sketch to ease visual load and form learned associations.](image)

Sodium is sometimes represented with reds in textbook illustrations and instructional drawings. Thus, I chose to associate ions concentrated outside of the cell with red-like tones, inspiring me to represent Ca\(^{2+}\) ions with pink. Potassium is sometimes represented with greens in textbook illustrations and instructional drawings; thus, I associate green-like tones with ions concentrated inside of the cell. The sizes of each ion represent their concentrations relative to one another—i.e., Na\(^+\) exists in higher concentrations than Ca\(^{2+}\). Incorporating multiple visual
features with each element in the sketch facilitates deeper processing of the information and
develop a network for each concept with multiple visual cues, strengthening the memory trace
for this learned concept. Retrieval of a memory trace is proportional to the frequency of its use.
Therefore, ascribing specific colors designated meanings for common concepts could help with
the interpretation of visual illustrations.

Because Na\(^+\), K\(^+\), and Ca\(^{2+}\) are commonly discussed throughout biology, chemistry, and
physiology, using the same color conventions for these ions consistently over time would create
a strong learned association or a pattern that is easily detected and recognized by the brain. This
may make the process of decoding elements in a sketch easier with practice by enhancing
predictability. This may decrease the amount of attention required to encode the elements in a
sketch. During acquisition and primary stages of learning, this effect may help students process
the elements in a sketch more quickly with less mental effort, freeing cognitive space to: a)
process foreign elements, b) interact deeply with the concept illustrated, and c) determine
relationships between a sketch’s parts and their connections to prior knowledge.

Learned associations involving color can also generate physiological and emotional
responses in people upon color perception (Gaines & Curry, 2011). Literature reviews from
Gaines & Curry’s study sum up common emotional and physiological responses of humans in
the event of color perception, such as:

a) Red
i) Physiological: increases blood pressure, respiration, heart rate, and sense of
smell. Also correlated with motor correlation and sacrum-dependent functions
(those concerning the base of the spine).
ii) Emotional Associations: excitement, happiness, anger, pain
b) Blue—
   i) Physiological: relates to hearing, smelling, and seeing. Lowers appetite, body temperature, and respiration.
   ii) Emotional Response: Calmness

c) Violet:
   i) Physiological: Correlated with top of the head and cerebral function; supports non-verbal tasks
   ii) Emotional Response: largely associated with wisdom and authority

Employing associative learning techniques using color and actively integrating them into learning environments enhances visual attention and encoding of visual features (Gaines & Curry, 2011; Gozli et al., 2015; Kumi et al., 2013). A study performed by Gozli, Moskowitz, and Pratt (2015), investigated the correlation between visual attention and associative learning. Results depicted that presenting the same color cues during information acquisition and testing can significantly reduce reaction times in visual search tasks compared to the use of incongruent and neutral color cues. This demonstrates that learned associations of visual features (i.e. color cues) can minimize visual search time and improve visual attention.

Incorporating color into academic environments can also enhance learning affect. Studies have shown that reds provoke a negative motivation and positively impact performance in detail-oriented attention tasks (Kumi et al., 2013). Conversely, blues heighten task-related motivation and drive creativity (Kumi et al., 2013). Corporations commonly take advantage of such findings within the color psychology field to attract customers and alter their disposition towards a product (Kumi et al., 2013; Dwyer, 1971).
Colors in academic illustrations may be used meaningfully or subjectively; however, consistency and common representations in cueing tend to enhance visual literacy (Griffard, 2013). A review by Gaines and Curry (2011) that the three most important features are contrast, purity, and balance. Using colors that are too similar, or low in contrast, to one another will make it more difficult to set visual elements apart. It is also more useful to use pure colors, those that are not mixed with various undertones or hues, as they tend to be more stimulating. However, in a sketch the use of too much color – extraneous color – is contraindicated because the mind constantly strives to sort and organize even the extraneous information. When too many patterns or colors are present, they become distractors, making visual search more effortful and inducing stress upon the learner (Gaines & Curry, 2011; Verghese, 2001). Therefore, ensuring there is a balanced amount of color in a sketch will have a more potent effect.

Methods

For the purpose of this study a sketch or drawing was defined as, “a learner-generated external visual representation depicting any type of content, whether the structure, relationship, or process, created in static two dimensions in any medium” (Quillin & Thomas, 2015). Data collection for this study was conducted through Think-Aloud interviews, survey distribution, and course artifacts. Interviews were conducted between Winter 2020- Spring 2022. Pilot interviews were conducted through Spring 2021 and interviews for data collection were conducted between Summer 2021-Spring 2022. All participants were chosen from pools of William & Mary students who had taken D2L intensive biology courses with Dr. Paul Heideman within the past three years. These courses required daily homework sketches, usually on at least four topics per assignment, and provided example videos on how to use D2L to illustrate problem-solving.
Certain exam questions in these courses also required the use of D2L. Students from each class were split into two groups: those who used color in sketching (Color group or C) and those who did not use color in sketching in submitted class homeworks (Low Color group or LoC). Though those in the LoC group did not use color in the sketched analyzed in this study, this does not mean they never use color at all. Thus, we categorized these students as the LoC groups as they use color in D2L less often than those in the C group.

Potential participants were found by analyzing submitted homework sketches for three different class days from the six biology courses (Appendix B).

Names of those who used color in their submissions were written into a spreadsheet and uploaded to a private Blackboard page only accessible to certified research assistants—Vasu Kasangra, Jolene King, Daiwik Munjwani, Dhairya Thakar, and David Smith—Dr. Paul Heideman, and the author. Note, students who:

- a) used a single colored pen in their sketches (i.e. all in red pen or all in blue pen)
- b) used a B/W scanner to submit sketches
- c) only used color in the header of their sketch
did not qualify to participate in the C category.

After accumulating a list of names, students who used color were emailed by Dr. Heideman with an interest form for participation. Solicitations were sent to participants after they had completed their course. Those who submitted the interest form were ascribed a C group identification number (CAS#) for conservation of their anonymity. Interested students were then emailed a Qualtrics survey (with targeted questions specific to the C group) and a consent form by a research assistant who would also conduct their interview. Those who completed the survey,
consent form, and interview process were compensated for their time with an amazon gift card depending on the duration of their interview:

- Interviews for Pilot Data: $8 for completing the survey and conducting an interview ≤ 25 mins
  - Additional $2 for interviews ≥ 25 minutes
- Interviews for Data Collection: $15 for completing the survey and conducting an interview ≤ 25 mins
  - Additional $2 for every 5 minutes gone over-time

Students who completed the interest form and survey, but did not engage in the interview process, were not compensated per the conditions listed in the consent form and email that was sent out.

Those who did not use multiple colors in their sketches were sorted into the LoC category. Lists of names were created for potential participants for this group based on those who did not use color in their submitted homework sketches in the courses listed above. Students were emailed by a lab member, and or Dr. Heideman with a link to a different Qualtrics survey (with a targeted list of questions specific to the LoC group). This group was not required to engage in an interview so long as their survey responses were descriptive enough to use for analysis. Those who completed the survey were compensated for their time with an amazon gift card of $15.
Surveys

All surveys in this study were created and distributed through Qualtrics.

C Group Survey (CSu), N = 39 — This survey was split into five sections:

a) Vividness of Visual Imagery Task Questionnaire (Appendix D, Q 1.10-Q1.42)

b) Questions were adapted from the Aphantasia Network

c) Questions about the student’s practices using color

d) Does utilizing color in sketches make the information easier or more difficult to understand?

e) Do you use color in every sketch?

2) Questions about the student’s exam prep practices

a) During an exam, do you visualize the content of your sketches?

b) Do you think using color in sketching makes it easier or harder for you to recall information during exam time?

3) Open-ended questions

a) Would you recommend this strategy – using color in D2L – to a peer?

Why or why not?

b) If you would recommend this strategy, what advice would you give to enhance your peer's approach?

c) Upload signed consent form and a sample sketch

4) (Color Blindness Assessment,)
5) (Demographic questions)

The sections of the survey labeled with parentheses above are parts of the survey that were added later in the semester after some responses were received. These new sections were placed at the end of the survey to avoid placement effects. This was added to our study to assess whether color blindness might affect our results. We used an online adaptation of the Farnsworth D-15 Color Arrangement assessment to identify the presence of color blindness in our participants. Participants who completed the survey prior to the addition of the color blindness test were emailed and asked to complete and screenshot their results in return for an additional $5 compensation. A detailed layout of this survey can be found in Appendix D, while the color blindness assessment can be found in Appendix F.

Demographic questions were not included in the survey until Spring 2022. While the goal of the study was to examine the proportion of students using color and their reasons for incorporating it into sketching regardless of their gender, sexuality, or race, this oversight was corrected in Spring 2022. Apparent gender (M/F) based on names and how students presented themselves in their interviews was used for preliminary assessments of gender in relation to the use of color. Due to the small sample sizes, data on the effects of gender or race/ethnicity were not examined beyond a preliminary review.

*LoC Group Survey, N= 24*—This survey was split into five sections:

2) The Vividness of Visual Imagery Task Questionnaire
a) Questions were adapted from the Aphantasia Network (Appendix E, Q 1.10- Q1.42)

3) Questions about the student’s sketching practices
   a) What was the first class you have sketched for?
      i) Have you sketched since this class?
         (1) If so
   b) Have you ever used color in your sketches?
      i) If so, do you continue to use color in your sketches?
         (1) If not, describe why you have stopped using color in your sketches.
      ii) If not, briefly describe why you do not use color in your sketches.

4) Willingness to Use Color Questions
   a) Would you be willing to try using color in your sketches?
      i) For those that already use color: Would you be willing to try using MORE color in your sketches?
   b) Do you think there are any costs of using color in sketching? Briefly list them/describe why or why not.
   c) Do you think there are any benefits of using color in sketching? Briefly list them/describe why or why not.

5) Questions on The Effect of Color
a) Do you think using color in sketching would make it easier or harder for you to UNDERSTAND information during exam time?

b) Do you think using color in sketching would make it easier or harder for you to RECALL information during exam time?

6) Demographic questions – Demographic questions were added to the survey because they may be useful in follow-up studies with larger sample sizes. A preliminary review did not find differences, and these data were not analyzed further.

7) Color Blindness Assessment – The frequency of color blindness (8% of men, 0.5% of women) suggests that 2-3 of my participants (N = 61, __% female) have a form of color blindness. However, individuals with color blindness use and respond to color, although not necessarily in the same ways when sketching for D2L. I hope to analyze these data before turning in my final thesis, but the likely small sample size of individuals suggests that I could not detect any meaningful differences.

Follow-up questions were programmed with logic and displayed to participants based on previous, multiple-choice responses. All students in this group displayed the same demographic questions and color blindness assessment as those in the CSu.
Sample Size & Demographics

39 students who formerly used D2L in one of Dr. Heideman’s courses responded to the CSu. Those who participated in pilots (N = 18) were asked to re-participate in data collection. Some of those who agreed were required to resubmit their survey responses (N = 8). Secondary responses were compared to initial responses to evaluate if previous exposure to the survey had an effect on responses, and some minor differences were found. Therefore, only initial responses were used in the analyses, as not all individuals responded twice. Of these 39 individuals, 23 were interviewed. In the survey of LoC individuals, the self-reported gender ratio was female 0.66 to 0.34 male. Approximately 72% self-reported as white, and 28% as students of color.

C Interviews (CIn)

Human Subjects: PHSC-2020-03-27-14233-pdheid. 23 participants from CSu engaged in this portion of the study.

Interview Prep—Survey responses were analyzed for each participant and interview questions were prepared accordingly. Researchers followed a detailed protocol that contains a list of follow-up questions to ask participants based on their survey responses (Appendix F).

Sample sketches were also analyzed prior to the interview to

a) evaluate color patterns the student used in their sketch and

b) ask clarifying questions regarding their color choices and practices. For example,

i) Why are some things colored but not others?

ii) Do two elements colored the same in one sketch indicate relatedness, or something else?
Each participant had their own folder in a shared google drive amongst our lab members which contained their uploaded sketches and interview questions. Folders were labeled by COLOR# for confidentiality purposes.

The Interview— All interviews were conducted virtually by Zoom. Terms and conditions of the study were restated to participants for clarification: students were notified that the interview would be recorded for our lab members to refer back to later for data analysis. Participants were given the option to turn off their cameras at any time if they felt uncomfortable. The first portion of the interview was used to ask for elaborative follow-ups based on their survey responses. A subset of these questions is listed here:

a) How do you use color in your sketches (in what ways, for what purposes)?
b) In your survey you stated you do not use color in all sketches, can you elaborate on why you use color in some sketches, but not all?
c) In your survey you stated that certain colors carry specific meanings to you, could you provide examples of which ones and what their meanings are (the full set of interview question can be found in Appendix F).

In the second portion of the interview, the student orchestrated a walkthrough of their submitted sketch and answered questions regarding their color choices and usage. Samples of potential questions include:

a) (if the submitted sketch was an e-sketch) Do you always use a tablet for sketching?
i) Do you believe how often or how many colors you use would change if you were sketching on paper?

b) Is this a sketch where you’ve used more, less, or a standard amount of color?

c) Can you explain your color choice for your placements of red, dark red, and blue?

Fig. 8: Participant sample sketch of the chambers of the heart that was analyzed for patterns in color use prior to interview conduction.

After this exercise, participants were asked to study their sketches for one minute and recall the details to the best of their ability. After studying the sketch, participants were asked if: a) they could visualize what they saw and b) the mental image of their sketch was in color. Participants were then asked to recite the details of the sketch including the mechanism they sketched, what elements were included, and what colors they were ascribed if any. We intended to analyze/evaluate accuracy of recall of sketched elements, however, we did not end up analyzing data for this portion of the study due to time constraints.

The third portion of the interview was an imagery task using a simple and more complex illustration (Fig 9). Students were asked to look at each image for 30 seconds. After each image was then unshared from the screen, participants were asked if: a) they could visualize what they saw and b) the mental image of their sketch was in color. Participants were then asked to recite
the details of each illustration and include the colors of each element visualized if that was a part of their mental image. As shown in Fig 9 below, image (A) was presented first and (B) was presented last. The goal of this portion of the interview was to evaluate whether a) recall was affected by whether an image had a large amount of color used somewhat arbitrarily in a sketch compared to a simpler image with elements that have socially ascribed colors, b) students have a higher tendency to encode and remember items with socially ascribed learned associations (i.e. orange/yellow sun, pink brain, red apple) first or items with arbitrary colors (i.e. red planet, green dancer, etc.). Data was collected for this portion of the interview but not analyzed due to time constraints.

In the closing portion of the interview, students were asked to answer the following:

a) Are you or have you ever been an artist (frequently engage in drawing, painting, etc)?
b) Do you consider yourself a visual person?
   
i) Do you think your imagery is typically vivid or blurry?

   c) Please try to recall the sketch you submitted in as much detail as possible (name all colors and elements you can remember).

**Storage**

The following information was stored in a shared Google Drive between my lab team and Dr. Heideman:

   a) Participant ID numbers and First, Last Names
   
   b) Interview Questions
   
   c) Protocols
   
   d) Coding templates and Excel sheets
   
   e) Affinity Notes.

The following items were stored in a confidential Blackboard page only accessible to my team members and Dr. Heideman:

   a) Participant contact information
   
   b) Interview recordings.

**Data Analysis**

Surveys and Interviews were analyzed qualitatively. Each interview was watched and coded by two different coders using an affinity note template on Google Docs. This template has:

   a) A list of questions asked during the interview
   
   b) A conventions key for response types
Each interviewer listened for participants’ responses and plugged in the proper convention in the answer space provided. There were three types of questions presented during the interview that were coded with their own formats:

1. Simple Response Questions (that can often be answered with a Yes/No)
   - Yes was coded using a 1
   - No was coded using a 0
   - Rarely was coded using a 2
   - Sometimes was coded using a 3
   - No Difference/Neither was coded using a 4
   - No responses coded using a 5
   - Questions that were not asked during an interview were coded using a 6

2. Use of Color in Sketching Conventions
   - These were created based on common response themes amongst participants in the pilot interview category. Responses frequently included more than one of these conventions, those whose answers did not have a convention ascribed to them were categorized under “Other”. Conventions used in this study are listed below:
     i. -CL = decreases Cognitive Load— students using phrasing such as making a sketch easier to think about
     ii. O = Organizes parts, connecting identical, related, or similar elements
     iii. - VL = decrease visual load— students using phrasing such as making a sketch easier to look at
     iv. ! = emphasize important features
v. N = networking/ connecting otherwise disparate ideas and concepts within a sketch

vi. LA = Learned association—Student associates color specifically with things they are learning

vii. Tr = help track moving parts—student refers to use of color to help track moving parts

viii. C= Complex (sketch)— student identifies a sketch or topic as complex

ix. S=Simple sketch— student identifies a sketch or topic as simple

x. T = time— student refers to the amount time taken or available to complete a sketch

xi. Adding 0 in front of something makes it negative of that thing
   • EX: 0T = no time
   • 0CP = no colored pens (on hand/available)

xii. U = (achieved) understanding — student refers to having acquired or achieved understanding of a sketched topic

xiii. Other
   • Researchers took notes on participants’ responses

Following the transfer of participants’ responses into the Affinity Notes template, coders copied their responses into an Excel spreadsheet. This was done twice: once in a ‘personal throwaway’ template used exclusively by that coder. Coders transferred their Excel responses into a ‘final coding spreadsheet’ alongside the second coder’s responses. Throwaway templates were used prior to inserting codes into the final template to avoid response biases when coding alongside a partner. A simple true/false algorithm (Appendix G) was used to evaluate similarities
and differences between each coders’ responses. If both coders coded for an interviewee’s response the same way, the algorithm would display a green cell that read “TRUE”, meaning their answers aligned with one another. If the coders coded for an interviewee’s response differently, the algorithm displayed a red cell that read “FALSE”, indicating that the coders needed to revise and discuss their answer differences. Coders allotted time to revise and discuss the discrepancies in their responses until their responses matched. Once all answers matched, final answers for each participant were input into a Qualtrics survey to ease the burden of analysis.

Vividness of Visual Imagery task scores (VVIS) were also coded in Excel. Participants were required to read a short passage describing a visual scene, and rate their ability to visualize the scene on a scale from 1 (as vivid as normal vision) to 5 (no image pictured at all). From the four imagery tasks in the survey, I averaged each participant’s responses as their mean vividness of visual imagery score. Students were categorized into three groups based on their mean VVIS: ‘vivid’, ‘moderate’, and ‘dull’ visual imagery. Those with ‘vivid’ imagery had an average score between 1-2.5. Those with ‘moderate’ visual imagery scores ranged from >2.5-3.5. Those with ‘dull’ visual imagery scores ranged from >3.5-5. These boundaries were established based on the scale provided by the Vividness of Visual Imagery Questionnaire, adopted by the Aphantasia Network (Appendix C) — where 1 was vivid as normal vision and 5 was no image pictured at all. VVIS’s were analyzed between LoC and C groups to examine whether a student’s tendency to use color in D2L was associated with a higher VVIS. Imagery scores were also analyzed in relation to:

a) responses on whether or not participants believe that color enhances their understanding and or recall, and

b) rankings for how much of the participant’s mental images appeared in color.
CAS 16 and CAS 56 were excluded from this analysis because, during the interview phase, they indicated they had responded as if the 1 (vivid) score was dull, and 5 (dull) score was vivid. This suggests a potential issue with the Vividness of Visual Imagery Questionnaire as published, as others may have made similar errors without detection.

**Statistical Tests**

The following statistical tests were used to compare results between LoC and C groups defining significance as p < 0.05:

a) Chi-squared analyses for 2-way contingency analyses
   (https://www.socscistatistics.com/tests/chisquare2/default2.aspx)

b) Log-likelihood Ratio Tests (G-Tests) for 3-way contingency analyses for
   http://vassarstats.net/abc.html

c) Student’s t-test (Microsoft Excel)
**Results**

Results from LoC and C group surveys and interviews are presented in the following order: (1) Patterns in acquisition of color use and retention of color use in D2L, (2) beliefs on how use of color in D2L affects understanding, (3/4) whether students use color in each sketch, and reasons for using more or less color in D2L, (5/6) whether color carries meaning for students, (7) whether the use of color changes from early to late stages of learning new content, (8) monochrome versus color visualization of sketches, (9) costs and benefits of using color for the C groups, (10/11) vividness of visual imagery in relation to using color in sketching and recall of sketches during exams, (12) costs of using sketching for the M group, (13) use of color in sketches on paper *versus* electronic media, (14) analysis of homework sketch uploads in relation to surveys and interviews.

1) **C Group Interview’s (CIn’s): Color Acquisition and Color Retention in D2L**

55% of C interviewees stated they have always used color for D2L; 45% reported they began using color in D2L over time. 78% of participants in the C group reported that they have continued to sketch throughout their academic careers. Meanwhile, 9% of interviewees have stopped sketching and 13% of interviewees rarely sketch. All interviewees in the C group reported using D2L exclusively in STEM-related courses; only two participants use D2L in non-STEM-related courses.

Of the 78% (18 participants) who continue D2L, 15 of them reported that they continue to sketch with color (Fig. 10). 12 of those who continue using D2L believe the way in which they have used color in their sketches has evolved over time (Fig. 10):
CAS55 – “when I was taking AP bio, it was more using color… just so you could fit more on the page like break up topics and make it less like messy and just able to like outline things and just condense as much material onto a big piece of paper as possible. And I think over time I've tried to use it more to like have colors have a certain association sometimes”.

A summary of these results and how they connect with one another is in the flowchart below (Fig. 10).

**Fig. 10:** Flowchart of C interviewees and their sketching practices over time. A) Percentages of interviewed participants that have used color in D2L and continued to use D2L at the time of their interview. B) Percentage of interviewed participants who have always used color in D2L.

2) **CSu, CIn, & LoC Survey Responses: Use of Color in D2L vs. Understanding**

A majority of students in all groups—those who use and do not use color—reported that incorporating color in D2L enhances their understanding of sketched content (95% of CSu participants (Fig. 11-A); 96% of CIn participants (Fig.11-B); 54% LoC participants). Only one
person in this study (from the LoC group) reported that color makes sketches harder to understand (Fig. 11-C). The remaining participants reported that: a) color made no difference, or b) they were unsure of the effect of color on understanding in D2L (the latter answer choice was offered to the NCSI group only) (Fig. 11).

A chi-square test was conducted to evaluate any difference in how color affects understanding amongst these three groups of participants. The “No Difference” and “Neither” groups were collapsed to remove categories with zero responses. There was a statistically significant difference between LoC/C participants and their tendency to state that color makes understanding easier ($\chi^2 = 19.7578$, $p= 0.000557$), suggesting that a belief in increased understanding is a reason that students use color in D2L. Conversely, those who do not use color in D2L are more likely to state that color makes no difference in their understanding of the material, suggesting students may not use color in D2L if they believe it will have no impact on
their understanding of a sketch.

Fig. 11: Responses on whether students believe that use of color in D2L makes their sketches easier to understand assessed by (A) Color Group Surveys (CSu), (B) Color Group Interviews (CIn), (C) Low Color Group surveys (LoC).

Students who were interviewed were asked why they believe the incorporation of color in sketches has an impact on their understanding. Enhanced organization of elements in a sketch was the most common reason for color facilitation of understanding of sketched concepts (69%);
followed by decreased visual load—students using phrasing such as making a sketch easier to look at—(50%), and decreased cognitive load—students using phrasing such as making a sketch easier to think about—(41%). Interestingly, one student also reported time taken to incorporate color increases their understanding. Other major factors for why color is incorporated by participants in D2L include for emphasis of important elements in a sketch (32%), to form learned associations with color and elements in a sketch (14%). For clarification, formation of learned associations signifies that the student is ascribing a specific element of a sketch with its own color. The concept of learned association in D2L was further described in a participant’s interview, as shown in the quote below.

CAS 34: “Color is kind of like a symbolic association…For some reason, I liked associating nucleophile with blue and then like electrophoresis like red and then like the main structural stuff as as black. So that way I could kind of know what I was looking at, like what pieces did what and kind of correspond to each other.”

Other factors listed by students contributed to < 15% of responses; all 9% of those in the “Other” category stated that color is used for aesthetic purposes.
Fig. 12: Reasons CIn students report that use of color in D2L increases their understanding of a sketched concept.

3) CSu and Interview Responses: Using Color in Every Sketch

Most students who incorporate color in sketching do not use color all of the time (84%) (Fig. 13-A and Fig. 13-B).

Fig. 13: Percentage of participants using color in every sketch assessed by (A) CSu and (B) CIn.
Those interviewed were asked follow-up questions about how they discern: a) when to incorporate color, b) when to incorporate more versus less color in a sketch: the most important deciding factor for when to add color was increased complexity of a sketched concept (67%; Fig 14-A). Complexity was defined by participants as sketches with elaborate mechanisms and/or systems that contain multiple elements, making them more difficult to understand. Other factors that contribute to participants’ motivations for adding color into a sketch were chosen by fewer than 20% of participants: organization, emphasis, useful at early stages of learning (responses by 60% those in the “Other” category), etc. (Fig. 14-A). When explaining sketches in which they do not use color, the simplicity of a sketched topic was the most common response. However, students also frequently responded that time constraints were a reason not to include color in D2L, as was better understanding of the topic.

**Fig. 14:** Interviewee’s responses for those who occasionally use color in D2L reporting reasons to use or not use color in a particular sketch. (A) Reasons for using color in a sketch. (B) Reasons for not using color in a sketch. The major difference between the results in (A) and (B) are highlighted within red boxes.

4) C and LoC Responses: Use of More vs. Less Color in D2L
Reasons for the amount of color used were similar to reasons for when to use color. The two factors affecting the amount of color used in sketching were the degree of complexity, simplicity, and understanding (Fig. 15-A and Fig. 15-B). They reported adding more color as sketches become more complex (78%), and less color in a sketch was mostly attributed to simplicity (60%) and acquired understanding (25%)—both related to participants’ reasons for not using color at all in a sketch (Fig. 14-B).

Fig. 15: Interviewee’s reasons for using more versus less color in sketching. (A) Reasons for use of more color. (B) Reasons for use of less color. Major differences between the results in (A) and (B) are highlighted with a red box.

Similarly, when students were asked directly whether complexity (or difficulty) and familiarity (or understanding) of materials affect the amount of color used in a sketch. 96% of participants reported using more color in a sketch if its content is more complex, and 75% of students use less color if they are already familiar with the material. Students used the word familiarity in the context of increased recall and understanding with the repeated review:

CAS02: “If I'm more familiar with it, it's not as colorful. So I guess [familiarity is] like… however how comfortable I am with the material.”
CAS 16: “Yeah, I think when I'm not very familiar with the material, I use more color. And then once the color helps me remember what I'm drawing, I can just do it all in pencil because I have a lot of components [of the sketch] in my head already.”

Fig. 16: CIn responses on whether complexity of a sketch and familiarity with a topic factor into how much color is used in a sketch. (A) Does complexity factor into how much color is used in a sketch? (B) Does familiarity factor into how much color is used in a sketch?

5) CSu & Interviews Responses: Do Students Ascribe Colors Specific Meanings

Those who use color were asked during their survey and interviews whether they use color simply as a visual tool or whether colors are ascribed certain meanings. 78-86% of students who ascribe color with meaning (Fig. 17, response “yes” or “sometimes”) when asked to provide examples of which colors are meaningful and what their significances are. The most commonly occurring color conventions were:

a) Blue to indicate deoxygenated blood or water

b) Red to indicate oxygenated blood, important information, or changes/abnormalities that occur in a pathway or system.
Fig. 17: Responses on whether students ascribe colors specific meanings assessed by (A) surveys and (B) interviews.

There was little overlap among students regarding specific meanings behind particular colors. Though students tend to use similar colors in their sketches: particularly red, orange, yellow, green, blue, pink, and purple, students mostly ascribe them unique meanings according to their personal associations with the color. For a subset of 16% of surveyed individuals and 21% of interviewees, color meaning is always arbitrary.

6) ClIn’s: Consistency Among Students Who Ascribe Meaning to Colors in D2L

Interviewees who ascribe colors specific meanings were also asked whether they attempt to keep these meanings consistent within the same sketch and between other sketches (Fig. 18). All interviewees from this study try to keep the meanings of colors consistent in their sketches to at least some extent (73% “Yes”, 27% “Sometimes”).
Fig. 18: Percentage of interviewees who keep colors consistent between sketches and within the same sketch.

Interviewees were also asked questions pertaining to their habits of color use when sketching is done for practice prior to exams. ~83% of interviewees practice their sketches before exams at least sometimes practice in color. Between 84%-85% of these individuals keep the meanings of colors in their practice sketches consistent with respect to their original sketch.
Fig. 19: Flowchart of the percentage of C students who use color in practice sketches and keep the meaning of colors in their practice sketches consistent with the colors in their original sketch.

7) CIIn’s: Stages in Which Students Incorporate Color into D2L

Interviewees most commonly report using color in their sketches at the early stages of learning about a topic (65% of responses), and less often at late stages (17% of responses), though a large subset of students use color across all learning stages (39% choosing “all stages of learning” (Fig. 20); the total is above 100% because respondents were permitted to choose more than one response). Early stages of learning were explained as: a) in-class note-taking, b)
homework and c) study guides. Later stages of learning included: a) practice sketches prior to exams and b) sketches on exams. Some students use color differently in each learning stage depending on the class or topic being learned. When explaining their choice of two answers, most commonly “early learning stages” and “all learning stages”, students explained that they used color mostly at early stages of learning, but sometimes also at late stages of learning (i.e. practice sketches prior to exams when still trying to acquire understanding).

<table>
<thead>
<tr>
<th>Participants’ Responses for Stages of Learning in Which They Use Color in D2L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Learning Stages</td>
</tr>
<tr>
<td>Late Learning Stages</td>
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<tr>
<td>All Stages of Learning</td>
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<tr>
<td>None</td>
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Fig. 20: Stages of learning in which C interviewees use color in D2L. Note: some interviewees use color in more than one stage of learning (e.g., mostly early but sometimes at later stages of learning), causing the total to be above 100%.

8) CIn’s: Student Visualization of Sketches During Exam Time
Nearly all interviewees sometimes or always visualize the content of their sketches during exam time (96%). Approximately the same percentage of these interviewees sometimes or always visualize sketched content in color (92%).

![Graph](image)

**Fig. 21:** CN responses on if participants visualize content from their sketches during exam time and whether their visualizations are in color. (A) Are participants visualizing sketches during exam time? (B) Are participants visualizing their sketches in color during exam time?

9) **CSu, CI, & LoC Surveys: Use of Color in D2L vs. Recall**

Most students in all groups—those who use and do not use color—reported that incorporating color in D2L enhances their ability to recall sketched content during exam time (Fig. 22). This was reported by 79-84% of C participants and LoC participants. Only one person in this study (from the LoC group) reported that color makes information harder to recall during test time. The remaining participants reported that: a) color made no difference, or b) they were unsure of the effect of color on understanding in D2L (the latter answer choice was offered to the NCSI group only). A chi-square test was conducted to test for differences in how color affects recall amongst these three groups of participants. The “No Opinion” and “Neither” groups were collapsed to reduce cells with few responses. There was no statistically significant difference
between LoC/C participants and their reports on whether color makes sketches easier to recall ($\chi^2 = 1.0412, p= 0.903482$). Namely, those who use color and do not use color in D2L are nearly equally as likely to state their expectation that color enhances recall of a sketched concept during exam time.

**Fig. 22:** Responses on whether students believe that use of color in D2L makes their sketches easier to recall during exam time assessed by (A) CSu, (B) CIn, (C) LoC surveys.

10) **CIn’s: Costs & Benefits of Using Color in Sketching**

The greatest costs of color use in D2L reported by C interviewees (78%) was the amount of time it takes to switch between colored pens and assign an object color; all other factors were
stated by fewer than 20% of students as costs of D2L. The most frequent benefit of color use in D2L reported was decreased cognitive load. 10 participants included “Other” benefits in their answer choices, the most frequent being that adding color in D2L increases their motivation towards learning (chosen by 6 out of 23 total participants).

11) **LoC v. CSus: Vividness of Visual Imagery**

LoC and C Participants were asked to complete a Vividness of Visual Imagery Questionnaire (VVIQ) during their surveys. Questions asked students to read a prompt and visualize the scene described. Students were required to rank their visualizations on a scale from 1 (highly vivid and clear image; as vivid as vision) to 5 (no image at all). These rankings were used to give each respondent an average vividness of visual imagery score (VVIS), depending on the mean of their scores from each of their responses. In these VVIS analyses, scores between 1.0-2.5 were considered vivid VVIS’s (‘vivid’); scores >2.5-3.5 were considered moderately vivid VVIS’s (‘moderate’); and scores >3.5-5.0 were considered dull VVIS’s (‘dull’).
Differences between the C and LoC groups were not statistically significant ($t=2.00$, $p=0.84$, df = 59).

**Fig. 24:** Mean vividness of visual imagery score (VVIS) comparison between C and LoC individuals, based on Vividness of Visual Imagery Questionnaire (VVIQ) results.

An analysis was also performed for comparison of participants with vivid, moderate, and dull VVI within surveyed C and LoC groups. There were no significant differences in the proportion of VVIS’s between the LoC and C groups were insignificant ($p=0.90$).
**Fig. 25:** VVIQ result comparison between the percent of CSu and LoC participants with vivid imagery, moderately vivid imagery, and dull imagery.

I also modified the VVIQ to include follow-up questions regarding a) whether or not their visualizations were in color, and b) how much of the scene was in color. A g-test analysis was performed to assess any relationships between those who use/do not use color in D2L, the amount of mental images that appear in color, and VVI scores. Results suggested there are no significant differences between the following parameters:

a) The C group and LoC group did not differ significantly in VVI scores (Log-Likelihood Ratio Test, $G = 0.28$, $p = 0.0833$, df = 17)

b) The C group and LoC group were not different in relation to the amount of color that appears in student visualizations (Log-Likelihood Ratio Test, $G = 4.44$, $p = 0.2177$, df = 17)

c) For the C group and LoC, the amount of mental images that appear in color in relation to the VVI scores of the two groups were not statistically significant (Log-Likelihood Ratio Test, $G = 2.54$, $p = 0.0833$, df = 17)
Fig. 26: Comparison of CSu and LoC individuals, their VVIS’s, and the amount of color that appeared in their mental images during the Vividness of Visual Imagery Questionnaire. (A) C participants with vivid vividness of visual imagery (‘vivid’). (B) LoC participants with vivid vividness of visual imagery (‘vivid’). (C) C participants with moderately vivid vividness of visual imagery (‘moderate’). (D) LoC participants with moderately vivid vividness of visual imagery (‘moderate’). (E) C participants with dull vividness of visual imagery (‘dull’). (F) LoC participants with dull vividness of visual imagery (‘dull’).

There was, however, a significant difference reported between participants’ VVI scores and how colored their visualizations are ($G = 14.98$, $p = 0.020$, $df = 6$). This suggests that mental
images are more likely to appear in color as VVI scores are more vivid, while only some/no images in color as VVI scores become more dull. However, my confidence levels for this comparison are reduced due to the non-significant p-value from the overall comparison of all three variables above (refer to point (c) above). Therefore, this test needs to be repeated for confidence in this result.

12) **LoC v. CSus: Vividness of Visual Imagery vs. How Color Use in D2L Affects Understanding of Material**

VVIS’s were also compared to participants’ responses regarding whether use of color facilitates or worsens understanding of a sketched concept. Most students in the C group (ranging from 91%-100%) reported that color makes sketched concepts easier (Fig 27-A). From the LoC group, only about half of participants stated that color makes sketches easier to understand (40%-62%) (Fig 27-B). A G-test was used to compare relationships between C/LoC groups, participants’ VVI scores, and their reports on how color affects understanding in D2LL. Results revealed the following:

a) No statistically significant difference in vividness of visual imagery scores amongst those who use color (C group) and those who use low amounts of color (LoC group) in D2L \( (G^2= 0.2, p= 0.0948, df= 2) \)

b) No statistically significant difference between VVI scores and whether color makes sketches easier to understand \( (G^2= 0.2, p= 0.0948, df= 2) \)

c) A significant difference between C/LoC groups and reports on whether color makes sketches easier to understand \( (p=0.0001) \). Specifically, those in the C group have a higher proportion of participants that believe color helps understanding compared to the LoC group.
Point (c) is further supported by the statistically significant difference in a comparison between all three variables ($G = 17.82, p = 0.0128, df = 7$), consistent with a significant difference amongst at least one pair of comparisons. This suggests that those who already use color in sketching have a higher tendency to use color because it enhances their understanding of sketched material; while those in the LoC group have less conviction that color influences their understanding of a sketch, decreasing their likelihood to adopt color in D2L.

![Graph](image)

**Fig. 27:** Comparison between the VVIS of surveyed COLOR and LoC participants and their reports on whether use of color in D2L makes sketches easier to understand during exam time. (A) COLOR. (B) LoC.

13) **LoC v. CSu: Vividness of Visual Imagery vs. How Color Use in D2L Affects Recall of Material During Exam Time**

The majority of C and LoC participants from each of the three types of VVIS’s reported that color increases their ability to recall information from a sketch during exam time. A G-test statistical analysis suggested no significant difference between these three groups ($G^2 = 1.14, p = 0.9922, df = 7$), providing no evidence that color’s affect on recall during exam time is related to a) one’s relative vividness of visual imagery or b) whether students use color in D2L.
Fig. 28: Comparison between the VVIS of CSu and LoC participants and their reports on whether use of color in D2L makes sketches easier to recall during exam time. (A) C group. (B) LoC group.

14) LoC: Sketching Patterns

All 24 surveyed students in this group were asked to answer questions about their former and current sketching questions. 88% of those surveyed have used D2L since the first class they have sketched in; of these individuals, 81% of participants continue using D2L in their courses. All participants in the LoC group were asked if they had ever used color in their sketches, 63% reported yes and 37% reported no. Of the participants that a) continue using D2L, and b) have used color in D2L before, about 50% report that they still use color. The other 50% of individuals rarely or never use color in their sketches.

43% of participants that still use color in D2L from this group reported that they use color less frequently than they used to. Responses as to why they these students use color less included: a) they no longer need color to distinguish elements of a sketch, or b) lack of time. One student mentioned that part of the reason color is no longer as necessary in sketching is because they have acquired a higher level of understanding in biology, “I mainly use color when distinguishing among major elements of the content. As I developed better background
understanding of certain topics, color stopped being necessary” (NCIS #151). This relates to participant responses from CI, that familiarity with material results in reduced use of color over time (ref. Fig 16-B).

Those who have never used color in D2L (37%) were also asked to state their reasons for not using color (Fig. 29). Interestingly, the most common responses (time constraint and lack of colored pens) are similar to the reasons that those who occasionally use color in D2L choose not to incorporate color into a particular sketch (ref. Fig 14-B).

Fig. 29: Reasons LoC survey participants do not use color in D2L.

15) **LoC: Costs of Using Color**

Surveyed individuals in the LoC group were asked a free response question that told them to briefly describe their reasons for not using color in D2L. Similar to the C group, the highest cost attributed to use of color in D2L was time consumption (70%). More people in this group also reported access to colored pens as a constraint (40%), compared to the 6% of C interviewees that reported access to colored pens as a constraint (ref. Fig 23-A).
Some participants also reported memory and cognitive costs to use of color. Results on the costs of color use in D2L according to LoC participants are well summarized by the following participant’s survey response to this question:

“Material costs: buying the coloring supplies. Temporal costs: spending time changing utensils. Memory cost: instead of jotting everything down as quickly as it comes into your head, you have to spend time considering how to best use your colors, where everything should go, and you lose some of the quickest details” (NCIS #119).

**Fig. 30:** Cost and benefits associated with color use in D2L according to LoC interviewees. (A) Costs.

16) **LoC & COLOR Students: Sketching on Paper versus Sketching Electronically**

Because costs and benefits of using color might vary by medium – paper or electronic device (whiteboard was also used, but by too few students to analyze) – we evaluated the proportion of students using paper versus e-media in relation to their propensity to use color in D2L. We used homework submissions from Day 5 and 36 of BIOL 302, Fall 2019. There was a
significant effect of medium for sketching on both days (Day 5: $\chi^2 = 18.6048$, $p < .00001$; Day 36: $\chi^2 = 31.0576$, $p < .00001$). In the two different uploads, one early in the course and one later in the course, nearly all students used color when sketching on an electronic device (90% and 100%, Fig. 31), but only a minority of students used color when sketching on paper (24% and 18%, Fig. 31).

**Fig. 31:** Percentage of students in BIOL 302 Fall 2019 who used color and did not use color in their submitted homework sketches when sketching on paper *versus* with a device (E-Sketch). Homeworxs analyzed were from (A) Day 5 of course material—or towards the beginning of the semester, and (B) Day 36 of course material—or towards the end of the semester.
Discussion

Many students incorporate color into their drawings without explicit instruction to do so. While color may be used only for aesthetics, color could be a beneficial learning aid. In this study, I explored the use of color as a visual aid in D2L, when it should be used, and the reasons students hesitate to use color. In the sections that follow, I will discuss the reasons students give for their use of color and relate my results to prior research on color and processing, learning, and memory.

Results from CIn and CSu groups were so similar the two are combined for this discussion and collectively referred to as the C group. That is to say, the ‘C group’ now encompasses all participants who use color in D2L from this study.

Finding #1: Use of Color as a Tool for Occasional Emphasis & Organization

The reason students most commonly use color is to organize various elements in a sketch or emphasize its critical features. However, even those that actively use color in D2L, do not use it on every occasion. In other words, students have identified points in which color is most useful and where color is not necessary. Instances in which students think it is important to incorporate color are weighted by two factors: complexity and degree of familiarity with material.

One reason students may favor using color with increased complexity relates to cognitive load theory (CLT). As identified by John Sweller, working memory stores are only capable of holding and manipulating a discrete amount of information at one time (Sweller, 1998). “Working memory has two well-known characteristics: When processing novel information, it is very limited in duration and in capacity” and nearly all information that is not rehearsed in working memory is lost within 30 seconds of being learned (Kirschner et al, 2006). Increased
cognitive load makes it difficult for the learner to isolate and understand the individual parts of a concept, hindering comprehension and performance. Sketches containing multiple elements or strands of events with varying interactions can make it hard for a learner to parse a sketch and differentiate key elements or strands from ‘background elements’, especially if there are no visual cues. Triesman’s feature integration theory states that focal attention to visual input results in an automatic visual grouping for the development of a general schema of the object; individual objects within the visual field are identified later as they are processed in higher-order processing centers for perception in the brain (Triesman, 1980; Hanna & Remmington, 1996). In the event of cognitive overload, illusory conjunctions are formed—or false correlation of features with parts of visual stimuli—mis-encoding the location of an object in space (Triesman, 1980; Hanna & Remmington, 1996). A solution to this issue might be to assign important objects in an illustration an easily distinguishable feature that groups like parts together. Because color is so easily perceived, it is a useful way to avoid cognitive/visual overloading: “varied colors of objects help segregate the world into meaningful objects” (Hanna & Remmington, 1996).

Students may be following Triesman’s theory of feature integration through use of color as an attentional tool for emphasis and organization, allowing them to condense the information being encoded into groups, freeing up more space in visual working memory stores and improving encoding by clustering related elements together. Color as a tool that improves learning efficacy was well encapsulated an excerpt from a review by Chang et al., 2018 regarding the impact of color on learning:

“Kumi, Conway, Limayem, and Goyal (2013) stated that color ‘can enhance the organization and presentation of information, decrease search times, and enable the identification and organization of information’ (p.5). Color is a clue that helps learners retrieve information (Hanna & Remmington, 1996;
Keller & Grimm, 2005). Compared with the monochromatic information, color-coded information visualizations can better support knowledge acquisition (Keller & Grimm, 2005).

Even without instructions, students appear to apply these principles to use color in ways that they feel improves learning.

The use of color as an organizational tool due to complexity corresponds to how students tend to use color more in the beginning and early stages of learning (i.e. note-taking, initial sketches, sketching in study guides), or when material is less familiar (in the sense of poor understanding; familiarity in the context of increased recall and understanding with the repeated review— definition from ‘Results’).

As familiarity with material increases, students have primed themselves with partial mastery of a sketch, decreasing cognitive load and therefore complexity, facilitating easier processing of sketched concepts. At this point in learning, elements of a sketch and their relationships to one another have already been grouped, encoded, and consolidated in memory; students may only need to glance at a sketch to jog their memory of a process. Therefore, students report that color is typically no longer necessary for organization and emphasis because understanding has already been acquired.

Finding #2: Color May Enhance Understanding for the Color Group but not for the LoC Group, While Enhancing Recall for both the LoC & C Groups

(a) Understanding— Nearly all C participants reported that color facilitates their understanding of a sketch. Understanding should improve with increased organization of parts in a sketch and emphasis of important elements would lead to a better understanding of materials. However, color has other effects that can improve learning comprehension. Attention and
engagement with materials are strongly correlated with the acquisition of understanding and knowledge by a learner, these are factors that work together to increase a student's level of mastery (Amarin & Al-Saleh, 2020; Chang et al., 2018; Imhoff, 2004; Gaines & Curry, 2011).

Multiple studies on the behavioral implications of color in learning environments have supported its ability to improve attention and academic performance (Gaines & Curry, 2011; Griffard, 2013; Imhof, 2004). Conversely, the use of monotonous cues in academic environments reduces learner engagement by a reported minimum of 25%, resulting in lower attention and performance (Engelbrecht, 2003; Gaines & Curry, 2011; Imhof, 2004). Color has been speculated to improve attention for reasons that include its natural property as a visual stimulant (focusing attention).

Improvements in understanding with color in learning are often correlated with enhanced engagement with materials (Amarin & Al-Saleh, 2020). Another literature review by Kumi et al. (2013) mentioned that color simultaneously enhances engagement and attention to materials by influencing affective states. For example, the use of color for merely aesthetic purposes increases learner engagement with material by improving motivation to study (Kumi et al., 2013). In the case of D2L, many students may have a low affective state towards sketching or a specific subject, but if they enjoy using color, the student may be more likely to spend more time trying to acquire an understanding of a sketched concept when color is incorporated as reported by 6 students in the C group. Color may also increase engagement with learning materials on a physical level—by physically coloring the object—and on a cognitive level—by forcing the student to spend time selecting colors for elements of a sketch and representing their relation to one another using the same or different colors). The act of choosing color to link related
elements or emphasize key elements focuses attention on relationships and features that build memory and proper formation of a schema.

The combination of increased attention and engagement induced by the use of color in D2L may possibly explain why C groups state that color increases their understanding. I postulate that this may be a result of higher focused visual attention, positive affect toward the material, and time spent studying material. However, future studies must be conducted to determine if these factors directly contribute to increased understanding in those that use color in D2L.

*(b) Recall*—Most students in C and LoC groups reported that they believe color makes sketches easier to recall. Since there was no statistically significant difference between these groups, there is not enough evidence that enhanced recall would be a significant enough reason to convince students to use color in D2L.

According to the literature, the effects of color may have this impact for a variety of reasons. Just as positive affect towards learning may improve understanding, as mentioned in the section above, it may also improve recall. For some, the addition of color in learning induces positive cognitive appraisal for a task, increasing mastery avoidance—the engagement with a task to avoid forgetting knowledge—and therefore increasing recall by making the learning experience more stimulating and enjoyable (Kumi et al., 2013). Correlations between attentiveness and recall have also been found applied in behavioral studies for marketing psychology: commercials presented to audience members in color had longer watch times and better recall than those in the black/white commercial group (Dwyer, 1971). More attention to and greater engagement with a stimulus increases our likelihood of remembering its details.
I hypothesize that one of the more important reasons color might enhance recall is due to the way networking of multiple cues to one memory has the ability to strengthen a trace (Dwyer, 1971; Martinez et al., 2010; Recantenesi et al., 2015). In other words, “The basic assumption of each of the realism theories is that learning will be more complete as the number of cues in the learning situation increases” (Dwyer, 1971). This is due to the fact that neural circuits activated during the encoding of a stimulus are also activated during retrieval (Martinez et al., 2010). When more cues, including color, are associated with a memory network, higher levels of activity occur within that network, easing the retrieval process.

(c) Recall vs. Understanding—Though only C participants reported higher levels of understanding from the addition of color in D2L, both C and LoC groups reported a belief in better recall from the use of color in sketching. This is an interesting result, given that understanding and recall are often perceived as interdependent processes, but are actually independent. A person may have nearly perfect recall as a result of the practice effect, but no understanding if they do not spend time reasoning with the parts of a sketch and how each element plays a role in the “big picture” of a process. Likewise, a student may understand the “big picture” aspects of a concept, but have poor recall of its details. Based on the differences presented between recall and understanding, it seems as though LoC students may think color is a helpful tool for recall because it better highlights the details of a sketch, improving recall—possibly by enhancing focused visual attention and distinguishing elements from one another.—. However, the LoC group might believe color is not essential to understanding a sketch because they are able to organize and analyze the relationships between elements of a sketch just as well without color, or with color. The C group, on the other hand, may feel that they need color to efficiently organize and analyze the relationships between elements of a sketch, facilitating their
understanding. This is well explained in a quote from a think-aloud interview with a student who uses color in D2L below:

CAS 31 [paraphrased for clarity]: looking at a picture with no color in it, or a graph makes it hard to see what's going on. Because for me… I guess everything looks the same when you first look at it, so color takes that extra step away from having to figure out what you're even looking at. Sometimes, it helps me to focus on one specific thing, and everything else will be in black and white because it's not important. And so that helps me a lot to focus my attention on one specific thing so I can see what that one specific thing is doing or how it's changing.

This hypothesis for the differences between these two groups requires further investigation on why/how color may help recall but not understanding for LoC participants but help both recall and understanding for C participants.

**Finding #3: When C Students Ascribe Color Meaning, They Are Usually Kept Consistent**

Most students who use color assign some sort of meaning to color at least some of the time. Occasionally, these meanings are derived from common socially occurring color conventions (i.e. red for oxygenated blood or a maladaptive process, blue for deoxygenated blood or water). Students much more frequently assign colors their own unique meanings. Meanings of colors may correspond with the learner’s personal experience with that color—i.e., their interpretation of what the color represents/how that color makes them feel.

CAS34 [paraphrased for clarity]: I'd say purple… I just assign purple a royal sort of color. So I use it for something that's really important and I should pay attention to.
Other times, the meaning behind a color may have been picked up over time due to practice or habit. For example, in a few cases, elements are colored according to their professor’s sketches. If their professor colored K⁺ ions in green for an entire semester, and the student mindlessly copied the sketch and colors exactly, the student will begin to associate K⁺ ions with green by habit. These associations tend to spill over into other courses, forming strong learned associations with these elements. While colors sometimes have these meanings, students usually only ascribe a few colors meaning, if any, while the meaning of every other color is usually arbitrary depending on the sketch:

CAS 44 [paraphrased for clarity]: If I redo a sketch, it could be a totally new set of colors...So, I think the important part is that the colors are different from one another, not so much what the actual color is or means.

Color is most advantageous when a) it is strongly associated with an idea or concept, b) “when sufficient processing time is allowed that the object enjoys conceptual, not just perceptual, processing” (Hanna & Remmington, 1996). Forming these associations and adding them into D2L increases the number of cues linked to a learned concept, facilitating further structural reorganization of cortical areas that form connections between the various cues associated with a sketch (i.e. motor process involved in drawing, any associations formed with color, visual memory stores that hold mental images of the sketch, verbal associations with a sketched process, etc.). Including a strong memory trace, a strong learned association for color, into a new memory network could by itself make that memory trace more accessible, if the node for that color association is stable and easily activated. Because ascribing an increased number of cues to
a memory is correlated with accuracy of recall, color may not only expand the semantic network for an idea, but increase the likelihood of its activation.

As mentioned above, incorporating color conventions in a sketch with strong personal or semantic associations may improve recall. In order for these associations to strengthen, it is important to keep associations consistent over time. The majority of students who ascribe meaning to color in D2L strive to keep these associations consistent within the same sketch and between sketches. This brings a greater advantage above enhancing the strength of learned associations: the advantage of pattern-finding as an inherent process of visualization. To increase the efficiency of visual processing and accurate visual representation, the mind strives to group information together and search for patterns within our environments, priming the mind and body with what to expect (Gozli et al., 2015; Keller & Tergen, 2005). Maintaining uniform associations for colors in between sketches might make it easier for the brain to identify patterns within an illustration, facilitating faster processing of visual elements—as a color association strengthens. As a result, I postulate that forming strong associations in D2L—by ascribing colors to recurring elements in a sketch that have consistent meanings—will lower cognitive and visual loads for students, making it easier for the learner to focus on relationships between elements in a sketch as opposed to having to spend cognitive real estate and resources on unpacking the elements in a sketch before their roles in a process. A constraint is that for some students, forming too many learned associations was perceived as counterproductive:

CAS02: “One thing is, is that some colors represent specific things. [It’s] really kind of annoying. So I can't use them all the time because they're [assigned to one meaning].”
This suggests importance in maintaining a balance between using colors arbitrarily versus using them to communicate a specific meaning.

**Finding #4: Time and Access to Colored Pens as Major Costs Associated With Using Color**

The strongest cost associated with use of color in D2L across both groups (LoC and C) was time. Nearly all students identified time as a physical constraint (the time it takes to physically switch between colored pens), and/or a cognitive constraint (the time it takes to choose a color for an element in a sketch). When students are pressed for time, i.e., when notetaking or taking exams, propensity to color in a sketch is decreased. However, if a student is not sketching on a time constraint, the additional time taken to use color may turn out to be more beneficial than harmful—i.e., via increased engagement. According to research by Hanna & Remington (1996), “color confers an advantage... when sufficient processing time is allowed that the object enjoys conceptual, not just perceptual, processing.” The time constraints deserve more testing on the extent to which color acts as a time constraint both physically and cognitively. My data showing that only 20% of students who sketch on paper use color, while nearly all using electronic devices to sketch use color suggests that electronic devices may reduce the physical constraint enough that the perceived benefits outweigh the costs of color use. Because those using e-devices nearly all use color, the cognitive constraint may be a lower cost than the physical cost. Because e-devices are more expensive than pen and paper, this finding suggests that differences in frequency and amount of color use between C and LoC groups may be due to socioeconomic reasons.

The second most common constraint reported was access to colored pens. If students do not have direct access to colored pens, they will often not go out of their way to incorporate
color. This constraint seems to be closely related to the platform students sketch on—paper or a device, specifically. Those that use paper are much less likely to incorporate color in D2L. I anticipate this is a result of an additional requisite to buy and have consistent access to colored pens/pencils. As noted above, nearly all students who sketch on devices incorporate color into their sketches, potentially because a wide array of colors are accessible at all times, requiring a simple tap to switch among colors.

**Limitations & Future Directions**

Small sample size associated with this study poses a limitation to our ability to generalize results and apply them to all students/learners. Further, the sample of students from courses using D2L by a single instructor limits generalizability. Since we have not been able to locate previous literature addressing our research question (the effects of color in D2L, specifically), it is not possible to put the results in a broader perspective. Follow-up studies are necessary to address the intricacies of color use in D2L.

Based on interviews conducted in this study, most students seem to use the term familiarity in the sense of repeated study to gain both understanding and recall, but some students might use the term familiarity only in the sense of having seen content many times. Any follow-up interviews should clarify students’ definition of familiarity (how often they have seen material, versus how comfortable they are with material) and ask them how familiarity compares to or differs from understanding.

Students who engage in follow-up surveys and interviews should also be more thoroughly questioned on why color may facilitate recall but not understanding, and vice versa.
This will provide grounds for how students separate between processes involved in acquisition of understanding and their ability to encode and recall information, providing more clear guidelines for how color affects each process (if at all).

The knowledge gained from this study can be applied to future studies that isolate and measure and the proposed costs/benefits of color use in D2L (i.e., recall, understanding, processing speed, time constraints, etc.), along with to the extent to which the use of color affects D2L. One potential experimental design that could be used to measure whether color actually improves recall could ask two groups of participants (LoC and C) to draw sketch a biological concept from a textbook passage. C participants would be provided with pens to eliminate the constraint of access to materials. Students would be given a standard amount of time to study the sketch in each group (i.e. 15 minutes) and asked to recreate the sketch after an hour, one week, and one month after being introduced to the concept. Experimenters could then analyze the data and compare recall/detail in sketches from the LoC and C groups respectively.

Another future study could split students into four groups—PAPER(COLOR, PAPER/LoC, E-SKETCH(COLOR, E-SKETCH NO COLOR)— and have them complete the same sketch on each platform. Students in each group could be timed to measure whether there are significant differences in the amount of time it takes to manually switch between colored pens on paper versus a device. Experimenters could also compare PAPER(COLOR and E-SKETCH(COLOR to see if one group incorporates more color in their sketches compared to the other.

PRELIMINARY RECOMMENDATIONS
I have preliminary recommendations for instructors and students regarding when and how to use color according to the findings in this study.

a) Incorporate color as a tool for emphasis and or organization in complex sketches.

b) Be aware that the time taken to group elements or emphasize parts of a sketch using color is part of learning.

c) Emphasize greater use of color in earlier learning stages when unfamiliar with the content materials to help with separation and grouping of the pieces of a sketch. Reduce color when redrawing for practice as the sketch becomes easier to comprehend.

d) Ascribe a few colors meaning for recurring concepts or ideas.
   
i) Within reason, try and keep the meanings of colors consistent within and between sketches to increase the chances of forming learned associations.

e) Use color when having the *time*, allowing careful thought about the process being sketched and the relationship between its parts.

f) If color is helpful, seek access to an e-device. For instructors, seek e-devices for students who lack access.
Acknowledgements

I would like to express my greatest gratitude to my advisor, Dr. Heideman for allowing me to spend three years in his lab studying what I love, even if it meant challenging his ideas. Dr. Heideman has been a more incredible mentor than I could have wished for, inspiring me to learn and grow as a researcher, student, and person. He truly has allowed me to “receive the best education I possibly can” through his guidance, and I hope to one day follow in his footsteps.

Thank you to the other members of my committee—Dr. Stevens & Dr. Keiffaber— for their collective time, patience, and feedback throughout this process. I look up to each of them immensely and they have all made this process one of the most rewarding and enlightening experiences of my academic career.

Thank you to my incredible team members: Vasu Kasangra, Jolene King, Daiwik Munjwani, and Dhairya Thakar. Working with each of them has made this process enjoyable and worthwhile. It would have been impossible for this project to come together as it did without them. A special thanks to Dhairya for not only being an amazing team member, but an incredible friend these last four years.

Thank you to my parents, Laura and Steven Cantarutti, for being, my biggest support system, incredible role models, and always pushing me to be the best version of myself. I could not be where or who I am today without either of them.

Thank you to my all my friends, at William & Marry and back home, who have supported me throughout this journey. Words cannot express how grateful I am to have such incredible people by my side.
Lastly, thank you, William & Mary. This institution and its opportunities have allowed me to maximize my academic potential more than I thought possible, for which I am forever grateful.
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https://doi.org/10.1007/11510154_9


https://doi.org/10.1207/s15516709cog0704_2


Appendix A: Think Aloud Interview Protocol/Script

WILLIAM & MARY
Department of Biology
Williamsburg, VA 23187
Summer & Fall 2021

Effect of Color on Sketching: Think Aloud Interview Consent Form

Dear Student,

Thank you for your interest in our research experiment on learning. If you agree to participate, you will be called upon to set up an interview in which you will discuss the usage and ascription of color in your sketches with the interviewer. Prior to the interview you will be asked to complete a survey. At the end of this survey you will be asked to upload a colored sketch you have created in the past of your choice—make sure you are not too unfamiliar with the content and be prepared to walk through your thought process.

Each interview session will be entirely virtual. The experimenter will ask you to talk through your thought process of using colors in sketching based on your submitted survey answers; please note that it makes no difference whether your answers were correct or not, we encourage all students to participate. Each session will be recorded for later analysis by the researchers.

Note that before any of your materials are analyzed by the interviewers (Juliana Cantarutti, Mary Kate Lantz, and Dhairya Thakar) your name will be converted to a unique code number. Your specific responses will not be shared with others in association with your name or with identifying information. Only the interviewers listed above will view the video sessions. Identifying information will be kept confidential between the interviewer and interviewee. Transcripts of the interviews will be identified only by a randomly chosen project number. The instructor for the course will not know which students choose to participate in this study and will not see the data until after the final grades are submitted at the end of the semester.

We will provide a copy of the final results to individual participants who request a copy. Your participation is completely optional, and you may opt out of the research at any point without any consequences. Upon completing the survey and virtual interview, you will receive an $15 total compensation, for interviews that last 25 minutes or less. For every 5 minute interval that your interview goes overtime, you will receive an additional $2 to your total compensation (i.e. 30 minutes = $17 total gift card ; 35 minutes = $19 toal gift card; etc.)
Should you agree to participate, interviews will be conducted virtually through Zoom in compliance with newly implemented COVID-19 policies; this will continue until the resumption of normal activities on campus. You will be able to select a time for your virtual meeting that is most convenient for you. This session may be recorded for data synthesis; however, any personal information will remain undisclosed as mentioned above.

If you have concerns or dissatisfaction with this research study, please contact Dr. Jennifer Stevens, chair of the WM Protection of Human Subject Committee (PHSC). Local telephone: (757) 221-2176, Toll free line: 1-888-905-0149.

Please contact Juliana Cantarutti at jfcantarutti@email.wm.edu, or Professor Heideman at 757-221-2239 and or by email at pdheid@wm.edu if you have questions. Thank you!

Juliana Cantarutti
Neuroscience | Biochemistry
The College of William & Mary, Class of 2022

Student: I, ____________________________, agree to participate in this experiment on learning. I understand that I may opt out of the test at any time without penalty.

Signature: ____________________________ Date: ____________
Appendix B: List of Biology Courses Participants Were Collected From

**BIOL 203**

- Fall 2018

**BIOL 302**

- Fall 2019
- Fall 2020

**BIOL 432**

- Spring 2019
- Spring 2020
- Spring 2021
Appendix C: David F. Marks Vividness of Visual Imagery Questionnaire—Adopted from the Aphasia Network

(Scale)
https://davidfmarkscom.wordpress.com/2020/03/10/vividness-of-visual-imagery-questionnaire-vviq/

The Rating Scale in the VVIQ

The five-point rating scale of the VVIQ is presented below. Some researchers prefer to reverse the numerical scale to make 5 = perfectly clear and as vivid as normal vision, and 1 = no image at all, you only “know” that you are thinking of an object.

<table>
<thead>
<tr>
<th>Rating</th>
<th>The Image Aroused by an Item Might Be</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Perfectly clear and as vivid as normal vision</td>
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<tr>
<td>2</td>
<td>Clear and reasonably vivid</td>
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<tr>
<td>3</td>
<td>Moderately clear and vivid</td>
</tr>
<tr>
<td>4</td>
<td>Vague and dim</td>
</tr>
<tr>
<td>5</td>
<td>No image at all, you only “know” that you are thinking of an object</td>
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</table>

(Questionnaire) https://aphantasia.com/vviq/
How vivid is your mind's eye?

VVIQ, the Vividness of Visual Imagery Questionnaire, explores the vividness of your visual imagination. It is proven to be an accurate test of the vividness for which you can see people, objects, or settings in your mind's eye.

**VVIQ Instructions**

For each scenario try to form a mental picture of the people, objects, or setting. Consider carefully the vividness of your visual imagery experience. Does some type of image come to mind? Rate how vivid the image is using the 5-point scale. If you do not have a visual image, rate vividness as ‘1’. Only use ‘5’ for images that are as lively and vivid as real seeing. The rating scale is as follows:

1. No image at all, I only “know” I am thinking of the object
2. Dim and vague image
3. Moderately realistic and vivid
4. Realistic and reasonably vivid
5. Perfectly realistic, as vivid as real seeing

✔ I agree to the privacy policy and terms.*
Think of some relative or friend whom you frequently see (but who is not with you at present) and consider carefully the picture that comes before your mind’s eye.

**The exact contours of face, head, shoulders and body.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

**Characteristic poses of head, attitudes of body etc.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

**The precise carriage, length of step etc., in walking.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

**The different colors worn in some familiar clothes.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing
Visualise a rising sun. Consider carefully the picture that comes before your mind’s eye.

The sun rising above the horizon into a hazy sky.
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

The sky clears and surrounds the sun with blueness.
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

Clouds. A storm blows up with flashes of lightning.
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

A rainbow appears.
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing
Think of the front of a shop which you often go to. Consider the picture that comes before your mind’s eye.

**The overall appearance of the shop from the opposite side of the road.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

**A window display including colours, shapes and details of individual items for sale.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

**You are near the entrance. The colour, shape and details of the door.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

**You enter the shop and go to the counter. The counter Assistant serves you. Money changes hands.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing
Finally think of a country scene which involves trees, mountains and a lake. Consider the picture that comes before your mind’s eye.

**The contours of the landscape.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

**The colour and shape of the lake.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

**The colour and shape of the trees.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing

**A strong wind blows on the trees and on the lake causing reflections in the water.**
- No image at all, you only “know” that you are thinking of the object
- Dim and vague; flat
- Moderately clear and lively
- Clear and lively
- Perfectly clear and lively as real seeing
Appendix D: Color Group Survey Questions

- What is your full name?

For each item in this section, try to form a visual image, and consider your experience carefully. For any image that you do experience, rate how vivid it is using the five-point scale provided in the graphic below. Please note that there are no right or wrong answers to the questions, and that it is not necessarily desirable to experience imagery or, if you do, to have more vivid imagery.

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</tbody>
</table>

- Q 1.10: Visualize a rising sun. Consider and carefully rate the vividness of the picture that comes before your mind’s eye *REMEMBER: rate using whole numbers only; use the graphic above as a guide* (1 is VIVID as normal vision; 5 is NO IMAGE):
  - The sun rising above the horizon into hazy sky
    - *Question has sliding scale ranging from 1-5*
- Q 1.11: Do you picture this image in color?
  - Yes
  - Somewhat
  - No
- Q 1.12: If so, how much of the image appeared in color?
  - Everything was in color
  - Most of it was in color
  - Some of it was in color
  - None of it was in color
- Q1.20: Visualize a rising sun. Consider and carefully rate the vividness of the picture that comes before your mind’s eye *REMEMBER: rate using whole numbers only* (1 is VIVID as normal vision; 5 is NO IMAGE):
  - Clouds. A storm blows up with flashes of lightning
    - *Question has sliding scale ranging from 1-5*
- **Q 1.21**: Do you picture this image in color?
  - Yes
  - Somewhat
  - No

- **Q 1.22**: If so, how much of the image appeared in color?
  - Everything was in color
  - Most of it was in color
  - Some of it was in color
  - None of it was in color

- **Q 1.30**: Visualize a rising sun. Consider and carefully rate the vividness of the picture that comes before your mind’s eye *REMEMBER: rate using whole numbers only* (1 is VIVID as normal vision; 5 is NO IMAGE):
  - The sky clears and surrounds the sun with blueness
    - *Question has sliding scale ranging from 1-5*

- **Q 1.31**: Do you picture this image in color?
  - Yes
  - Somewhat
  - No

- **Q 1.32**: If so, how much of the image appeared in color?
  - Everything was in color
  - Most of it was in color
  - Some of it was in color
  - None of it was in color

- **Q 1.40**: Visualize a rising sun. Consider and carefully rate the vividness of the picture that comes before your mind’s eye *REMEMBER: rate using whole numbers only* (1 is VIVID as normal vision; 5 is NO IMAGE):
  - A rainbow appears
    - *Question has sliding scale ranging from 1-5*

- **Q 1.41**: Do you picture this image in color?
  - Yes
  - Somewhat
  - No

- **Q 1.42**: If so, how much of the image appeared in color?
  - Everything was in color
  - Most of it was in color
  - Some of it was in color
  - None of it was in color

- **Q 2.10**: Does utilizing color in sketches make the information easier or more difficult to understand?
  - Easier
  - More Difficult
  - Neither
• Q 2.20 When creating sketches do you use color in EVERY sketch?
  o Yes, I use color in every sketch
  o No, I don’t use color in every sketch
• Q 2.30: Do colors carry a specific meaning to you? (Ex: blue always means hydrogen bonding)
  o Yes
  o Sometimes
  o No

• Q 3.10: Do you practice your sketches before an exam
  o Yes
  o Sometimes
  o No
• Q 3.20: During an exam, do you visualize the content of your sketches?
  o Yes
  o Sometimes
  o No
• Q 3.30: Do you think using color in sketching makes it easier or harder for you to recall information during exam time?
  o Easier
  o Harder
  o About the Same
• Q 4.10: Would you recommend this strategy to a peer? Why or Why not?
  o * Open ended*
• Q 4.20: If you would recommend this strategy, what advice would you give to enhance your peer's approach?
• Q 5.10: Please upload a PDF or photograph of one of your sketches in preparation for your interview with us. NOTE: *Make sure it is a sketch you are comfortable with explaining your GENERAL thought process for
• Q 5.20: Please SIGN our consent form (using the link below) and attach a PDF/photograph below
• Q 5.30: One last thing: Please take a quick color blindness test using the link below. Once you are done, click "Show Me My Results". Screenshot and upload them below!
Appendix E : Low Color Group Survey Questions

- What is your full name?

For each item in this section, try to form a visual image, and consider your experience carefully. For any image that you do experience, rate how vivid it is using the five-point scale provided in the graphic below. Please note that there are no right or wrong answers to the questions, and that it is not necessarily desirable to experience imagery or, if you do, to have more vivid imagery.

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- Q 1.10: Visualize a rising sun. Consider and carefully rate the vividness of the picture that comes before your mind’s eye *REMEMBER: rate using whole numbers only; use the graphic above as a guide* (1 is VIVID as normal vision; 5 is NO IMAGE):
  - The sun rising above the horizon into hazy sky
  - *Question has sliding scale ranging from 1-5*

- Q 1.11: Do you picture this image in color?
  - Yes
  - Somewhat
  - No

- Q 1.12: If so, how much of the image appeared in color?
  - Everything was in color
  - Most of it was in color
  - Some of it was in color
  - None of it was in color

- Q1.20: Visualize a rising sun. Consider and carefully rate the vividness of the picture that comes before your mind’s eye *REMEMBER: rate using whole numbers only* (1 is VIVID as normal vision; 5 is NO IMAGE):
  - Clouds. A storm blows up with flashes of lightning
- *Question has sliding scale ranging from 1-5)

- Q 1.21: Do you picture this image in color?
  - Yes
  - Somewhat
  - No

- Q 1.22: If so, how much of the image appeared in color?
  - Everything was in color
  - Most of it was in color
  - Some of it was in color
  - None of it was in color

- Q 1.30: Visualize a rising sun. Consider and carefully rate the vividness of the picture that comes before your mind’s eye *REMEMBER: rate using whole numbers only* (1 is VIVID as normal vision; 5 is NO IMAGE):
  - The sky clears and surrounds the sun with blueness
    - *Question has sliding scale ranging from 1-5)

- Q 1.31: Do you picture this image in color?
  - Yes
  - Somewhat
  - No

- Q 1.32: If so, how much of the image appeared in color?
  - Everything was in color
  - Most of it was in color
  - Some of it was in color
  - None of it was in color

- Q 1.40: Visualize a rising sun. Consider and carefully rate the vividness of the picture that comes before your mind’s eye *REMEMBER: rate using whole numbers only* (1 is VIVID as normal vision; 5 is NO IMAGE):
  - A rainbow appears
    - *Question has sliding scale ranging from 1-5)

- Q 1.41: Do you picture this image in color?
  - Yes
  - Somewhat
  - No

- Q 1.42: If so, how much of the image appeared in color?
  - Everything was in color
  - Most of it was in color
  - Some of it was in color
  - None of it was in color

- Q 2.10: What was the first class you sketched for extensively (this does not have to be a WM class, you may answer high school or earlier if applicable)?
  - ** Open Ended***

- Q 2.20: Have you sketched since this class?
  - Yes
- Q 2.30: Do you continue to use sketching to learn? LOGIC: If, Have you sketched since this class? Yes, Is Selected
  o Yes
  o No
- Q2.40: During an exam, do you/did you visualize the content of your sketches?
  o Yes
  o Sometimes
  o No
- Q 2.50: How vividly are you able to visualize the content of your sketches during exam time?
  o *Question has sliding scale ranging from 1-5
- Q 2.60: Have you ever used color in your sketches?
  o Yes
  o No
- LOGIC:

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<th>Display this question</th>
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<tbody>
<tr>
<td>If Have you ever used color in your sketches? Yes Is Selected</td>
</tr>
<tr>
<td>And Do you still use color in your sketches? Never Is Not Selected</td>
</tr>
</tbody>
</table>

Q 2.61 Do you still use color in your sketches?
  o Always or Almost Always
  o Sometimes
  o Infrequently
  o Almost Never
  o Never

- LOGIC:

<table>
<thead>
<tr>
<th>Display this question</th>
</tr>
</thead>
<tbody>
<tr>
<td>If Have you ever used color in your sketches? Yes Is Selected</td>
</tr>
<tr>
<td>And Do you still use color in your sketches? Never Is Not Selected</td>
</tr>
</tbody>
</table>

Q 2.62 Do you use color less frequently than you used to?
  o Yes
  o No

- LOGIC:
Q 2.63: Briefly describe why you use color less frequently than you used to in your sketches.

** Open Ended**

- LOGIC:

Q2.64: Briefly describe why you have stopped using color in your sketches.

- LOGIC:

Q2.65: Briefly describe why you do not use color in your sketches.

- Q 3.10: Are your sketches mostly made on
  - Paper
  - A Tablet
  - Other

- Q 3.20: Do you think switching your sketching platform (i.e. from e-sketch to paper sketch; vice versa) would affect the likelihood of you using color?
  - Yes
  - Maybe
  - No

- LOGIC:

Q 3.30: Would you be willing to try using color in your sketches?

  - Yes
  - Maybe
  - No
Q3.40: Would you be willing to try using MORE color in your sketches?
   - Yes
   - Maybe
   - No

Q 3.41: Under what circumstances would you be willing to try using color in sketching?

**OPEN ENDED***
LOGIC:

Q 3.42: Under what circumstances would you be willing to try using MORE color in sketching?

** OPEN ENDED***

LOGIC

Q3.43: Briefly explain why you wouldn't be willing to try using color in sketching.

Q 3.50: Do you think are any costs of using color in sketching? Briefly list them/describe why or why not.

Q 3.60: Do you think are any costs of using color in sketching? Briefly list them/describe why or why not.

Q 4.10: Do you think using color in sketching would make it easier or harder for you to UNDERSTAND information during exam time?
   - Easier
   - Harder
   - About the Same
   - Difficult to say/No Opinion

Q 4.20: Do you think using color in sketching would make it easier or harder for you to RECALL information during exam time?
   - Easier
   - Harder
   - About the Same
   - Difficult to say/No Opinion

What is your age?

Choose one or more races that you identify with:
- Which of the following best describes your current gender identity?

  - Female
  - Male
  - Transgender Female
  - Transgender Male
  - Prefer not to disclose
  - Nonbinary
  - Other

- Please take a quick color blindness test using the link below. READ THE INSTRUCTIONS IN THE FIRST TWO PARAGRAPHS! Once you are done, click "Show Me My Results" >> "Give me more detailed results". Screenshot and upload them below!
Appendix F: Think Aloud Interview Protocol/Script

Think Aloud Checklist

Prior to Interview

- Ascribe Participant ID (use this ID during your notes for interview) : CAS#
- Make sure consent form was submitted on survey
- Analyze survey + write down relevant questions according to their answers
- Analyze sketch
  - write down questions// points of clarification
  - Look for patterns in the sketch (are any colors repeated? What percent of the sketch is in color?)
- Create a folder with CAS# in the drive
- make a document for notes taking
  - have date of interview ; how long it took (exact) ; participant ID #
- Pull up their sketch

During

- Have YOUR camera on (even if they don’t have theirs on)
- RECORD the interview

After

- Upload the following to the drive
  - the recording
  - sample sketch
  - audio
- Label the date of interview on folder!
- Email heideman with
  - name of participant
  - email of participant
  - length of interview (how much time did it take)
  - $ amount for gift card
  - \( \leq 25 \text{ minutes} = \$15 \)
  - \( \geq 25 \text{ minutes} = +\$2 \) for every 5 minutes that you go overtime
i.e. $17 for 30 minutes; $19 for 35 mins

**KEY**

- = reminders for the interviewer
*** = survey questions

**Pre-Interview Protocol**

- Make sure participant signs consent + payment forms
- Ask participant to email you a colored sketch from class to walk through during the session (along with forms)
- Make sure to give the participant a unique code based on their interview time (CAS#)

**Open Ended Survey Responses**

[copy and paste their responses for questions 4.1 & 4.2 on survey here]

**Color Blindness Results (from survey, [Color Arrangement Test – Colblindor](#)):**

![Color Arrangement Test](image)

A very well known and established type of color blindness tests are hue discrimination or arrangement tests. This type of test uses the fact that colorblind people mix up colors along the so called Gaussian lines.

What do you have to do? Arrange the colored squares in the correct color by picking the most similar color from the choice below. You can order them by dragging the color squares into the upper boxes. Start with the pilot, which is already set.

You should be aware of that any type of online color blindness test is very dependent on your display settings and ambient light. You should visit your local eye specialist to get a correct diagnosis. If you take the test under different conditions you will recognize that the results can vary.

The test above simulates the D-15 dichotomous test which was introduced by Farnsworth in 1947. It aims to divide people into two groups, slightly colorblind and not colorblind people which pass the test and all others who fail it.

- Is the participant color blind?
  - If yes: what type
The Interview

○ **ASK ALL:** Is this the first class you have used sketches for? Can you clarify what class this was/is.
  ○ Did you always use color in this class or is it something you acquired over time?

○ Have you used sketching since this class?

○ If **NO**… why have you stopped sketching?

○ If **Yes** …
  ○ In what classes do you/have you sketched in?
  ○ Have you incorporated color in sketches since this class?

If **YES**

  ○ Is it the same amount, more or less color than used in this course?

If **NO**… why have you stopped incorporating color in sketches?

○ **ASK ALL:** Have you always used color in sketches, or is it something you started using overtime?

○ **ASK ALL:** Do you feel the way you have used color has evolved over time?

  If **Yes** … How?

1. **THEIR SKETCHING PRACTICES** — refer to sketch on the screen upload to survey
· **ASK ALL:** How do you use color in your sketches (in what ways, for what purpose)?

· Does sketching with color make things easier to understand? **
INTERVIEW>> How/Why?

· Do you use color in *all* sketches? ****

· INTERVIEW FOLLOW UPS >>
  · if **YES**
    · Why do you use color in all your sketches?

· If **NOT**...
  a. Why use color in some sketches, but not all?
    a. How do you discern when to use color in your sketches?

· **ASK ALL:** INTERVIEW>> In what scenarios do you typically find yourself using more colors? What about less color?

· **ASK ALL:** Does the complexity or simplicity of a sketch factor into how much color you use?
  o If **YES**... How so?
· **ASK ALL:** How about familiarity with material?

· Are there any colors that carry specific meanings? ***
INTERVIEW FOLLOW UPS>>

- If **YES** or **SOMETIMES**...
  - Which ones? What are their meanings?
  - When do you use consistent \( \text{v arbitrary colors} \)?
  - For recurring concepts or elements:
    - Are colors usually kept consistent between sketches?
    - Are colors consistent within the same sketch?

- If **NO**...
  - Do you keep track of what colors mean in your sketches? If so, how?
  - Does it ever matter what colors you use for a specific sketch?

- Do you have any “go to colors”? What are they?

- Do you practice sketches prior to the exam? ****

INTERVIEW FOLLOW UPS>>If **PRACTICE** sketch before exam

- Do you always, sometimes, or never practice them with color?

  If Practice **WITH** color

  - Does the meaning of the colors usually stay consistent between and with respect to the original sketch?

    - If **SOMETIMES**: when (do you use consistent \( \text{v arbitrary colors} \) with respect to the original sketch)?
If Practice **SOMETIMES WITH** color

a. When do you practice with vs. without color?

a. Does the meaning of the colors usually stay consistent between and with respect to the original sketch?

i. **SOMETIMES:** when (do you use consistent vs. arbitrary colors with respect to the original sketch)?

If **NEVER** Practice w/ color = NO FOLLOW UP

If **DO NOT PRACTICE** sketch before exam

How do you study a sketched concept in preparation for an exam?

   Ex: Do you verbally walk yourself through the process? Look at the original sketch? Visualize your original sketch?

**• ASK ALL:** In what stages of learning do you typically use color (you can answer all or none if applicable)?

   Ex to clarify if they have questions: early stages of learning (acquisition of material), later stages of learning (study and mastery)

   • When specifically (provide examples of when, where, how)?

1. **SKETCHING HABITS DURING EXAMS**
Do you visualize/create a mental image of the content from your sketches? ****

**INTERVIEW**>> If **YES** or **SOMETIMES**…
· Do you visualize them in color?
· How vividly are you able to visualize color and how well can you correspond them with content in sketch?

If **SOMETIMES** visualize in color…

· What types of sketches do you tend to visualize in color vs. not visualize in color?

If **NEVER** visualize sketches

· What is your process for recalling information during exam time?
· EX: Do you: verbally walk through the process in your head, use acronyms/mnemonics, combination of things, other, not sure?

Do you think using color in sketching makes it easier or harder for you to **recall** information during exam time? ****

· **ASK ALL:** INTERVIEW FOLLOW UPS>> Why? How?

**CLOSING QUESTIONS**
· **ASK ALL:** Do you feel there are any short term and long-term costs and or benefits to using color?
· **ASK ALL:** Do you think anything would change if you were to STOP using color in your sketches?
1. **INTERVIEW>> ANALYZING SKETCHES** Have the sketch they sent pulled up for reference

- **TASK:** Can you walk me through your sketch?
- **If it is** an e-sketch…
  - Do you always use a tablet for sketching?
  - Do you believe how often or how much color you use would change if you were sketching on paper?
- **If it is a paper sketch…**
  - Do you always use paper?
    - Do you believe how often or how much color you use would change if you were e-sketching?

- **Is this a sketch where you’ve used more, less, or a standard amount of color?**
  - on a scale from 1(not at all) -5 (very), how complex would you rate the contents of this sketch?
  - on a scale from 1(not at all) -5 (very), how familiar were you with the material in this sketch when you made it?
- **Are there any colors in here that have ‘universal meaning’ to you?**
- **Questions specific to patterns in their sketch**

  **TASK:** Eyes closed exercise
  1. Ask to look at the sketch for a minute (set timer)
  2. Remove sketch from screen
  3. Ask to close eyes
  4. Ask them the following
     - Can you visualize your sketch?
       - Is it in color?
         - What is in color?

**IMAGERY TASK**
• Ask them to look at the sketch for 30 secs (use timer)
• Remove sketch from screen
• Ask them to close their eyes and recall the sketch.
• Ask the following questions:
  ○ Can you visualize the drawing?

**If YES:**
  • Is it in color?

**If so ...**
  • List all items you remember in color and what colors they were
  • List all items you remember seeing (whether colored or not)
  • Are there any colors you remember seeing in the sketch disregarding their corresponding objects?

**If NO**
  • How are the items in the drawing coming back to you?
  • What did you see?
    • List all items you remember seeing (whether colored or not)
    • List all items you remember in color and what colors they were
    • Are there any colors you remember seeing in the sketch disregarding their corresponding objects?

**PILOT QUESTIONS**

• Are you or have you ever been an artist (frequently engage in drawing, painting, etc)?
• Do you consider yourself a visual person?
  ○ Do you think your imagery is typically vivid or blurry?
• Ask to remember sketch sample at end (color + detail)
Appendix G: Excel Coding Template & Guide

A) Make sure all coders have their own throwaway templates to code into prior to transferring information into the Final Coding Template
B) Use the following algorithm to quickly compare Coder 1 and Coder 2’s responses—TRUE indicates answers match; FALSE indicates answers do not match.
   a) =COUNTIF([cell range], [first cell in cell range])=2
      i) Example: =COUNTIF(C7:D7,C7)=2

Link to Coding Template (Unrestricted Access):

   TEMPLATE - TA CODING (COPY & PUT INITIALS IN FRONT)

Sheet 1 (Q1)

<table>
<thead>
<tr>
<th>Question #</th>
<th>1.a</th>
<th>Question #</th>
<th>1.b</th>
<th>Question #</th>
<th>1.b.i</th>
<th>Question #</th>
<th>1.b.i.i</th>
<th>Question #</th>
<th>1.b.i.i.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>First class sketched for?</td>
<td>always use color in this class?</td>
<td>sketched since?</td>
<td></td>
<td>Is what time do classes do you sketch?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAS</td>
<td>Response</td>
<td>CAS</td>
<td>Response</td>
<td>CAS</td>
<td>Response</td>
<td>CAS</td>
<td>Stim</td>
<td>Other</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question #</th>
<th>1.b.i.2</th>
<th>Question #</th>
<th>1.c</th>
<th>Question #</th>
<th>1.c.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Used color in sketches since?</td>
<td>Always used color, or started using overtime?</td>
<td>Way use color evolved overtime?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAS</td>
<td>Response</td>
<td>CAS</td>
<td>Response</td>
<td>CAS</td>
<td>Response</td>
</tr>
</tbody>
</table>
### Sheet 2 (Q2)

<table>
<thead>
<tr>
<th>Question</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>How color used (ways + purposes)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[alphabetical order]</td>
</tr>
</tbody>
</table>

### Sheet 3 (Q3)

<table>
<thead>
<tr>
<th>Question</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Does sketch w/color make easier to understand?</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Sheet 4 (Q 3.a)

**COLOR MAKES EASIER TO UNDERSTAND**

<table>
<thead>
<tr>
<th>Question</th>
<th>3.a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why easier to understand w/ color?</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[alphabetical order]</td>
</tr>
</tbody>
</table>
### Sheet 5 (Q 3.b)

**COLOR NOT MAKE EASIER TO UNDERSTAND**

<table>
<thead>
<tr>
<th>Question</th>
<th>3.b</th>
<th>Why NOT easier to understand w/ color?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS</td>
<td>Response</td>
<td>[alphabetical order]</td>
</tr>
</tbody>
</table>

### Sheet 6 (Q 4)

<table>
<thead>
<tr>
<th>Question</th>
<th>4</th>
<th>Do you use color in every sketch?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS</td>
<td>Response</td>
<td></td>
</tr>
</tbody>
</table>
### Sheet 7 (Q 4.a)

**USE COLOR IN EVERY SKETCH**

<table>
<thead>
<tr>
<th>Question</th>
<th>4.a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why use color in every sketch?</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[alphabetical order]</td>
</tr>
</tbody>
</table>

### Sheet 8 (Q 4.b.ii)

**DOES NOT USE COLOR IN EVERY SKETCH**

<table>
<thead>
<tr>
<th>Question</th>
<th>4.b.ii</th>
</tr>
</thead>
<tbody>
<tr>
<td>How do you discern when to use color in your sketches?</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WHEN USED .....</th>
<th>NOT USED .....</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[alphabetical order]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[alphabetical order]</td>
</tr>
</tbody>
</table>
Sheet 9 (Q 5)

**Question :** 5.i
When do you use MORE color?

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Question #:** 5.ii
When do you use LESS color?

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sheet 10 (Q 6)

**Question :** 6
Does complexity factor into how much color?

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sheet 11 (Q 7)

<table>
<thead>
<tr>
<th>Question</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does familiarity factor into how much color?</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sheet 12 (Q 8)

<table>
<thead>
<tr>
<th>Question</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do certain colors carry meaning?</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sheet 13 (Q 8 Y/S)

**IF ANSWERED YES OR SOMETIMES TO Q8**

<table>
<thead>
<tr>
<th>Question 8.i</th>
<th>What do they mean?</th>
<th>Question 8.ii</th>
<th>Are these meanings consistent?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS Response</td>
<td>[each color separate row]</td>
<td>CAS Response</td>
<td></td>
</tr>
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</table>

Sheet 14 (Q 8 N)

**IF ANSWERED NO TO Q8**

<table>
<thead>
<tr>
<th>Question 8.i</th>
<th>Do you keep track of what colors mean?</th>
<th>Question 8.ii</th>
<th>Does it ever matter what colors you use?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS Response</td>
<td></td>
<td>CAS Response</td>
<td></td>
</tr>
</tbody>
</table>
### Sheet 15 (Q 9)

<table>
<thead>
<tr>
<th>Question 9</th>
<th>Do you have any “go to” colors?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS</td>
<td>Response</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 9.a</th>
<th>What are they?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS</td>
<td>Response [alphabetical]</td>
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</table>

### Sheet 16 (Q 10)

<table>
<thead>
<tr>
<th>Question 10</th>
<th>Do you practice sketches before exams?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS</td>
<td>Response</td>
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</table>

<table>
<thead>
<tr>
<th>Question 10.i</th>
<th>Do you practice them with color?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS</td>
<td>Response</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 10.i</th>
<th>Meaning consistent wrt original sketch?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS</td>
<td>Response</td>
</tr>
</tbody>
</table>
### IF ANSWERED SOMETIMES TO Q10.i

<table>
<thead>
<tr>
<th>Question</th>
<th>10.i</th>
</tr>
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<tbody>
<tr>
<td>Meaning consistent wrt original sketch?</td>
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<table>
<thead>
<tr>
<th>CAS</th>
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</table>

### Sheet 17 (Q 11)

<table>
<thead>
<tr>
<th>1 = EL</th>
<th>2 = LL</th>
<th>3 = All</th>
<th>0 = None</th>
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</thead>
<tbody>
<tr>
<td>Question</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stages of learning color is used in?</td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>CAS</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[numerical order w/ comma]</td>
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## Sheet 18 (Q 12)

<table>
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<tr>
<th>Question</th>
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<th>Question</th>
<th>12.a</th>
<th>Question</th>
<th>12.a.i</th>
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<tbody>
<tr>
<td>Visualize sketch content during exam?</td>
<td>CAS</td>
<td>Response</td>
<td>CAS</td>
<td>Response</td>
<td>CAS</td>
</tr>
<tr>
<td>Do you visualize them in color?</td>
<td>CAS</td>
<td>Response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vivid?</td>
<td>CAS</td>
<td>Response</td>
<td></td>
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## Sheet 19 (Q 13)

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<tbody>
<tr>
<td>Easier recall?</td>
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Sheet 20 (Q 14)

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<tr>
<th>CAS</th>
<th>Cost</th>
<th>Benefit</th>
</tr>
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<tbody>
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<td></td>
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Sheet 21 (Q 15)

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<thead>
<tr>
<th>CAS</th>
<th>Response</th>
</tr>
</thead>
</table>

**IF ANSWER YES TO Q15**

<table>
<thead>
<tr>
<th>Question 15</th>
<th>Would anything change if stopped color?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS</td>
<td>Response</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 15.a</th>
<th>What would change if stopped?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS</td>
<td>Response [alphabetical]</td>
</tr>
</tbody>
</table>
Appendix H : Think Aloud Coding Conventions & Affinity Notes Template

Affinity Notes Guide

1) Copy the template below FOR EACH INTERVIEW
   a) Label The Doc as CAS# (your initials)—Affinity Notes

2) Add the doc to to the proper participant folder
   a) Go to the shared drive >> Interview Notes + recordings >> For Data Analysis >> Add to
      CAS# folder

3) Listen to an interview (only up until the sketch walkthrough! )

4) Follow along and ONLY
   a) Use Number system for yes/ no answers
      b) Take bulleted notes (do not add conventions in yet)

5) Record TIMESTAMP for when sketch analysis begins at bottom of doc

6) Once finished listening GO BACK AND MATCH CONVENTIONS TO RESPONSES MADE
   BY THE PARTICIPANT!

________________________________________________________________________

Straight Forward Responses : Number Conventions

    0  = no
    1  = yes

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    2= rarely
    3 = sometimes
    4 = no difference
    5= no response
    6 = Question Not asked

yes/no
Categories/conventions
Qualitative notes
CODE ON EXCEL

Use of Color in Sketching Conventions

- CL = decreases Cognitive Load
- O = Organizes parts
- VL = decrease visual load
- ! = emphasize important things
- N = networking/connecting ideas and concepts within sketch
- LA = Learned association
  - Student associates color specifically with things they are learning
- Tr = help track moving parts
- C = Complex (sketch)
- S = Simple sketch
- T = time

Adding 0 in front of something makes it negative of that thing
  - EX: 0T = no time
  - 0CP = no colored pens (on hand/available)
- U = (achieved) understanding
- F = familiar
  - 0F = unfamiliar

Other
  - ** take notes — what specifically
1. First class use sketching?
   **Note what kind of class

   Yes, first class in college. BIOL 203 (intro bio)

   a. Did you always use color in this class?

   Maybe 50% of the time

   b. Have you used sketching since this class?

   i. If NO… why have you stopped sketching?
   1. QUOTES IF INTERESTING

   ii. If Yes…
   1. In what classes do you/have you sketched in?
      o STEM
      o OTHER

   2. Have you incorporated color in sketches since this class?

   c. Always used color in sketches, or started using overtime?

   i. Do you feel the way you have used color has evolved over time?

   Probably, use color to add key concepts if he thinks it's needed.

   ii. If Yes … How?
   **take bulleted notes

   2. How do you use color in sketches (in what ways, for what purpose)?
   ** Use conventions + take brief notes on specifics / quotes

   3. Does sketching with color make things easier to understand?

   Yes, because it helps you recall better when using the sketching format- purely a memory thing.
a. If Yes
   * Use conventions + take brief notes on specifics / quotes

b. If NO. WHY?
   ** Take notes

4. Use color in every sketch?

No. Some sketches are very simple, some sketches are more complex. Again, if lots of concepts, maybe use color to show the key concepts.

   a. If Yes … Why?
      ** Take Notes

   b. If NO
      i. Why use color in some sketches, but not all?
         ** Take Notes

      ii. How do you discern when v when not to use color in your sketches?
         1. Use:
         2. Not Use:

Do not use color when simple, use color when more complicated.

5. When do you use more v less color?
   * Use conventions + take brief notes on specifics / quotes

6. Does the complexity or simplicity of a sketch factor into how much color you use?
   YES

7. Does the familiarity with material factor into how much color you use?
   YES

8. Do certain colors carry meaning?
    YES / S
    i. What do they mean?
ii. Are these meanings consistent/the same in every sketch? 

Not always- but it depends on the colors he used earlier in the drawing

If NO...

i. Do you keep track of what colors mean in your sketches? 

1. If Y, how? 

** Take Notes

ii. Does it ever matter what colors you use for a specific sketch? 

Sometimes yes, sometimes no

9. Do you have any “go to colors”? 

a. What are they?

10. Practice sketches before an exam? 

Y / S practice sketch

i. Practice them with color? 

Y

○ Meaning color consistent wrt original sketch? 

** If answer S = take note on when use consistent v random colors

S- SOMETIMES

a. When do you practice with vs. without color?

i. WITH - more difficult content might use color

ii. WITHOUT - less difficult content

○ Meaning color consistent wrt original sketch? 

Yes

** If answer S = take note on when use consistent v random colors

N = NO FOLLOW UP
N practice sketch

ii. How do you study sketched concepts?

11. Stages of learning color used in? ** Use conventions + take brief notes on exact stages of learning color used in (i.e. do they mention using color in: lecture notes, study guides, practice, on exams, etc)

   a. EL = early learning (note taking, acquisition and understanding—i.e. Note cards, study guides, etc.) - but if complex use more often until you have it mastered
   b. LL = later (practice, mastery, exam)
   c. A= all
   d. N= none

12. Visualize content from sketches during exam? Y/S

   a. Colored?

      i. Vivid (well able to correspond color with element in sketch)?

         S

      1. What types of sketches do you tend to visualize in color vs. not visualize in color?
         ** take notes

         N

      i. How do you recall information from sketch?
         **Take notes

13. Easier Recall? Y/N

   a. Why/Why not?

14. Costs + Benefits?
    **Take notes

   a. S (cost):
   b. ✔ (benefit):

15. Change if you stop using color?
a. What?

** Take notes

(TIMESTAMP) — SKETCH BEGINS AT: