<u>"DOES THAT MAKE SENSE?": A MIXED METHODS STUDY INVESTIGATING HIGH SCHOOL PHYSICS STUDENTS' USE OF METACOGNITION WHILE SOLVING PHYSICS PROBLEMS</u>

by

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A Dissertation
Submitted to the
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The Requirements for the Degree
of
Doctor of Philosophy
Education

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Fairfax, VA

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Dedication

This is dedicated to Dr. Deborah Roudebush. Deborah and I were both "new to the school" teachers when we met. We worked together, along with a couple of other amazing physics teachers, to rebuild and revamp the physics program at our school in an attempt to encourage all students to take a physics class. In doing so, Deborah pushed me to rethink my teaching style, challenge my understandings, and have more confidence in myself. The seeds that sprouted this dissertation were planted in our many conversations in her classroom. Her friendship and support were the reason I had the confidence to walk away from a career I loved to start a journey of growth towards a new career path.

Acknowledgements

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Acceleration*	a
Acceleration due to gravity*	g
Advanced Placement	AP
Centripetal acceleration*	a_c
Change*	Δ
Coefficient of friction*	μ
Cognitive Reconstruction of Knowledge Model	CRKM
Conceptual Change Model	CCM
Coronavirus disease 2019	COVID-19
Dynamic Model of Conceptual Change	DMCC
Force*	F
Force of friction*	F_f
Initial velocity*	v_o
Institutional Review Board	IRB
Intial position*	x_o
Kilograms*	kg
Mass*	m
Meters*	m
Meters per second*	m/s
Meters per second squared*	m/s^2
Normal Force*	F_N
Physics Metacognitive Inventory	PMI
Position*	x
Radius*	r
Standard deviation	SD
Sum*	Σ
Time*	t
Velocity*	v

*Abbreviation included in the Physics Problems for Think-Aloud in Appendix E

Abstract

"DOES THAT MAKE SENSE?": A MIXED METHODS STUDY INVESTIGATING HIGH SCHOOL PHYSICS STUDENTS' USE OF METACOGNITION WHILE SOLVING PHYSICS PROBLEMS

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Students come to their high school physics classroom with experiences and knowledge that can be used to help explain physics concepts, but those experiences may not fully align with the scientifically accepted science concept. When there is a misalignment between a student's prior knowledge and the scientifically accepted concept a misconception can occur. Conceptual change theory explains that before a student shifts their prior understanding, they must be dissatisfied with their prior knowledge. The process of being dissatisfied with their prior knowledge requires the student to evaluate their current conception by engaging in metacognition. The purpose of this mixed methods study is to better understand how seven high school physics students use cognition, metacognition, and dissatisfaction while solving physics problems to address misconceptions and prompt conceptual change. Data collection included quantitative and qualitative measures of metacognition. The Physics Metacognitive Inventory (PMI) was used to measure participants' reported use of physics metacognitive problem solving strategies. A think aloud protocol was used to document participants' cognition and metacognition while solving physics problems. Analysis included descriptive statistics of the PMI, coding of the think aloud, a joint display comparing quantitative and qualitative analysis, a similarity matrix heatmap displaying the overlay of physics problem solving steps and metacognition processes, and a case for each participant. Results found that each participant had their own problem solving style and way of engaging with cognition, metacognition, and dissatisfaction while solving the problems. Overall, participants were most likely to engage in metacognition during the planning phase of problem solving with comprehension monitoring being the most used metacognitive process. Participants were categorized in two ways. First, they were categorized as conceptual, computational, or hybrid based on what type of physics knowledge they relied on while solving the problems. Second as either an arrow or iterator based on how they moved through the problems. There were two types of dissatisfaction statements shared in the seven think aloud interviews, internal dissatisfaction and external dissatisfaction. Each of the seven participants expressed at least one statement of dissatisfaction during their think aloud interview. Participants were most likely to be in the planning phase of problem solving prior to and immediately following their statement of dissatisfaction, specifically choosing a concept or equations. Emergent themes from the think aloud address how participants used (a) teacher influence and expectations, (b) problems as assessments, and (c) common sense and logic as part of their cognition and metacognition while solving physics problems. Implications and future research will be discussed.

Chapter One

From a constructivist perspective, students do not come to their first physics lesson as an empty vessel waiting to be filled with new knowledge (O'Donnell, 2012). New knowledge is built from prior experiences and existing knowledge (Hewson, 1992), and students arrive at their first physics class with a wealth of experiences from everyday phenomena that can be used to explain physics concepts (Disessa, 1996; Gunstone et al., 1992; von Aufschnaiter & Rogge, 2010; Vosniadou, 1994). Students also come to physics class with exposure to physics vocabulary, such as velocity, acceleration, energy, and work, without fully understanding how these words are defined within the context of physical science (Wade-Jaimes et al., 2018). These experiences impart a combination of beliefs, observations, and mental models which help shape students' preexisting knowledge of physics (von Aufschnaiter & Rogge, 2010; Vosniadou, 1994). In the literature on physics education, this preexisting knowledge is referred to using a range of terminology such as: (a) prior knowledge, (b) prior conceptions, (c) misconceptions, (d) missing conceptions, (e) alternate conceptions, (f) alternative frameworks, (g) intuitive knowledge, (h) folk knowledge, (i) prior experiences, and (j) preconceptions (Disessa, 1996; Eryilmaz, 2002; Gunstone et al., 1992; Posner et al., 1982; Sherin, 2006; Taasoobshirazi & Sinatra, 2011; von Aufschnaiter & Rogge, 2010; Vosniadou & Mason, 2012). As many of those terms suggest, the prior conceptions a student brings to class may not fully align with the scientifically accepted physics concepts.

Students learning new physics concepts initially rely on their previous interactions with everyday phenomena to understand the new material. While the beliefs and conceptions formed from these prior experiences can help students make connections to new concepts or ideas, the connections the students make are sometimes misleading or incomplete (von Aufschnaiter & Rogge, 2010). A misalignment between the student's prior conception and the physics concept being taught blocks progress towards an understanding aligned with the scientifically accepted understanding of that concept (Hammer et al., 2005) and can result in a misconnection (von Aufschnaiter & Rogge, 2010). A misconception is an erroneous interpretation of a scientific concept (Vosniadou & Mason, 2012). A misconception may cause a student to think they understand the concept because they have made a connection, but it is a partial misunderstanding or a complete misunderstanding. These misaligned prior conceptions make new physics concepts more difficult for students to understand (von Aufschnaiter & Rogge, 2010). Students with misconceptions may need more support to fully understand the scientifically accepted physics concept.

Students misconceptions can develop in multiple ways. Some students come to class with a misconception already formed from repeated experiences with the physics phenomena in everyday life (von Aufschnaiter & Rogge, 2010). Some misconceptions are formed in class and are a result of students connecting new concepts learned in class in real time to the first association that comes to mind (Rowlands et al., 2007). When a student is learning a new concept, they try to relate it to something they are familiar with or have experienced. If they do not have an appropriate experience to connect to the new concept, a misconception can be spontaneously formed (Rowlands et al., 2007). Additionally, if a student has a correct, but weak, understanding of a concept, they can be convinced by a peer that the peer's incorrect understanding of the concept offers a better explanation of the concept than their own correct conception (Wade-Jaimes et al., 2018). This creates a situation where a student's correct conception shifts to become a misconception.

Some students may need to experience a physics concept multiple times from various viewpoints to be confident in their understanding (Wade-Jaimes et al., 2018). The process of shifting from a prior understanding that does not properly align with the scientifically accepted conception to a more complete conceptual understand is a gradual process that may take multiple iterations (Vosniadou & Mason, 2012). When teachers expose students to physics concepts through multiple experiences and exposures, students have more time to check their own mental models and work towards an alignment with the scientifically accepted physics concept (Wade-Jaimes et al., 2018). Unfortunately, due to lack of time spent on science in elementary school, most students lack opportunities to experience physics during their K-12 education.

Many students do not have a large quantity of time to learn science, let alone physics in an academic setting. Elementary students average only 20 minutes of science a day. This science instruction is split between life science, earth/space science, and physical sciences, which includes both chemistry and physics (Plumley, 2019). While roughly 40% of students have the opportunity to take a single-discipline science course in middle school, physics tends to again be combined with chemistry in a physical science class (Havekost, 2019). This amounts to very little time budgeted for physics instruction in elementary and middle schools, creating a space where many students do not have formal school exposure to physics concepts until high school. This means a high school physics class may be the first time students experience physics in a way that challenges their prior conceptions of physics which is problematic given that many students need multiple experiences with a physics concept to develop a deep understanding (Vosniadou & Mason, 2012; Wade-Jaimes et al., 2018). Further, in many traditional physics classes, the focus of the class is mathematically solving physics problems rather than conceptually understanding physics concepts (Mulhall & Gunstone, 2012), meaning that with the focus on problem solving rather than conceptual understanding, students may not have the explicit opportunity or support to evaluate their misconceptions.

Although there are few opportunities before high school to engage in physics, high school physics teachers can help students grapple with their prior knowledge. A majority of high school physics teachers believe the pre-existing knowledge students bring to class is an important part of their physics education. Sixty-five percent of the physics teachers who participated in the 2018 National Survey of Science and Mathematics Education agreed that students' prior knowledge and skills promote effective instruction (Banilower, 2019). Unfortunately, only 45% of physics teachers reported that they actively work to understand students' prior knowledge (Banilower, 2019). It is important for teachers to understand their students' prior experiences relating to a concept so they can tailor their teaching in a way to better address the misconceptions and help facilitate a shift in students' conceptual understanding towards an understanding that aligns with the scientifically accepted concept (Hewson, 1992).

Knowing that students come to class with a wide variety of prior knowledge, a physics teacher can provide all students with a common experience in the classroom that better aligns with the new concept. These experiences are an attempt to bridge the gap between the students' real-world experiences and the physics concepts (Redish & Hammer, 2009; Sherin, 2006; von Aufschnaiter & Rogge, 2010). By engaging students in experiences that more appropriately align with the scientific understanding of the new concept, students are able to create immediate, correct connections to the concept rather than choosing a prior experience that may not be an appropriate connection.

Not only is it helpful for teachers to engage with students' prior conceptions, it is also helpful for students to metacognitively engage with their prior conceptions (Dimmitt & McCormick, 2012; Rozencwajg, 2003). Teachers can provide students with opportunities to engage with and reflect upon their own prior knowledge. Reflecting on one's own understanding is a type of metacognitive experience that can provide students opportunities to add to, revise, or delete from their knowledge base (Flavell, 1979). If students are given the support to be metacognitive, they can evaluate the usefulness of their prior conceptions and gauge if those prior conceptions help or hinder learning. In a typical high school physics classroom this is not a common practice. "It is somewhat striking that, in contrast to what is known from learning theory about the importance of reflection, only 24 percent of physics classes have students write reflections on what they are learning" (Banilower, 2019, p. 19). Without metacognitively engaging with and reflecting on their prior knowledge, students may struggle to shift their prior conception to be better aligned with the scientifically accepted conception.

The purpose of this proposed research study is to better understand how students use metacognition in physics, specifically during problem solving. Understanding how students use metacognition while solving physics problems will give insight as to how students use problem solving to start the process of shifting their current conceptions towards the scientifically accepted understanding of a concept. In Chapter 2, I will define problem solving in physics and explain the theoretical framework of conceptual change. Conceptual change defines the process a student undergoes when they are shifting their current conception. Next, I will define metacognition and summarize research on metacognition within the field of physics education. This will shed light into what has already been studied and what gaps exists in the literature. In Chapter 3, I will illustrate a proposed mixed methods research study that investigates high school physics students' use of metacognition while solving physics problems. In Chapter 4, I will explain the data sources, data analysis, and answer the two research questions. And finally in Chapter 5, I will connect the findings of Chapter 4 to existing literature and share conclusions.

Chapter Two

Problem Solving

Problem solving has many definitions depending on the discipline. From a psychology lens, problem solving applied generally is a cyclical process that involves seven steps: (a) identifying the problem, (b) defining and representing the problem, (c) developing a solution strategy, (d) organizing knowledge about the problem, (e) allocate resources, (f) monitor progress, and (g) evaluate the solution for accuracy (Pretz et al., 2003). Problems can be categorized into two classes: well-defined and ill-defined problems. Well-defined problems are those whose goal is distinct, and solutions tends to be straightforward. An ill-defined problem is one that the goal is not clearly outlined, making identifying and representing the problem difficult (Pretz et al., 2003). Ill-defined problems tend to have multiple solutions while a well-defined problem may only have one.

For the purpose of this study, physics problem solving is defined as a well-defined word problem that has one or more unknown quantities for which students are expected to solve for or calculate. In a traditional physics classroom, solving physics problems the main focus (Kim & Pak, 2002; Mulhall & Gunstone, 2012). Solving a physics problem is a multistep process that involves both physics conceptual understanding and mathematical skills, specifically algebraic manipulation (Kuo et al., 2013) and encourage the use of metacognitive strategies (Abdullah et al., 2013). The process of solving a typical physics problem involves understanding the phenomena at hand, picking the appropriate concept or equation, using algebra to manipulate and solve the equation, and then using conceptual reasoning to check the validity of the answer (Kuo et al., 2013). Physics problem solving requires both physics content knowledge and problem-solving strategies (Nandagopal & Ericsson, 2012). Even though there are aspects of solving physics problems that potentially use conceptual understanding, students do not necessarily gain conceptual understanding from learning to solve problems (Fink & Mankey, 2010; Kim & Pak, 2002; Mulhall & Gunstone, 2012). A student who can correctly solve a problem mathematically may not fully understand the underlying physics concepts involved in the problem (Nandagopal & Ericsson, 2012), creating a gap in knowledge between the use of the equation and the associated physics concepts (Kim & Pak, 2002). One study found that even after solving over 1000 physics problems, students still had misconceptions about physics concepts (Kim & Pak, 2002). Many students try to find an equation that fits their problem rather than the underlying concepts (Lucas & Lewis, 2019). In doing so, these students are not engaging in understanding the concept or addressing misconceptions while solving the physics problem. Students who are successful in understanding physics are able to better select the tools needed to solve a physics problem rather than just follow proscribed steps (Kuo et al., 2013).

Most physics textbooks suggest similar steps to the ones explained above when solving a physics problem (Etkina et al., 2014; Knight, 2013). First, students are encouraged to show their understanding of the concept represented in the problem by creating a diagram or sketch. Next, students are asked to organize their knowledge of the physics problem when they list their known quantities for the problem as well as what unknown quantity they are being asked to solve for. Students then choose the appropriate concept or equation needed to solve the problem. After choosing the equation or concept, students should solve for their unknown variable using algebra manipulation. Once the equation is solved for the unknown, the students plug in their known numbers with appropriate units. Finally, the students calculate their answer with correct units, including checking to make sure that their units and answer match the phenomena in question (Etkina et al., 2014; Knight, 2013).

When approaching a problem, students tend to identify, define, and represent the problem in terms of what they already know (Pretz et al., 2003). This causes a problem when their prior knowledge and experiences do not properly align with the scientific concept addressed in the problem (von Aufschnaiter & Rogge, 2010). A misalignment between the student's prior knowledge and the knowledge needed to solve the problem could cause the student to evaluate their own understanding. If this self-evaluation leads the student to be dissatisfied with their existing knowledge, the students will start the process of conceptual change (Dole & Sinatra, 1998; Posner et al., 1982). And the process of conceptual change is productive if it works to move the student towards the scientifically accepted conception.

Conceptual Change

Students come to class with a "great deal of experience that is relevant to the study of physics" (Sherin, 2006, p. 535), but not all of those experiences align with physics concepts as they are taught in physics classes (Sherin, 2006). Students can build from, restructure, and/or shift their previous conception of physics to better align with scientists' conceptions of physics as a result of their experiences in the classroom. This process is known as conceptual change. Conceptual change refers to both the resulting change in understanding and the learning process that leads to that change (Chi et al., 1994; Dole & Sinatra, 1998; Slotta et al., 1995).

When a student finds a discrepancy between their own conception and the scientific conception, there are three choices a student can make: assimilate their knowledge, accommodate their knowledge, or maintain their current conception. Assimilation, or extension (Hewson, 1992), occurs when a student uses the new conception to build upon their prior conception. The new knowledge merges with the students' old knowledge to enrich or add to their ideas (Posner et al., 1982; Vosniadou, 1994). Accommodation, also referred to as an exchange (Hewson, 1992), happens when a student replaces, revises, or reorganizes their prior conception based on the new conception (Posner et al., 1982; Vosniadou, 1994). While assimilation and accommodation can both involve blending prior knowledge with new knowledge, in assimilation, the resulting conception tends to look more like the prior conception while accommodation is a more radical change where the resulting conception is more similar to the new conception (Posner et al., 1982; Vosniadou, 1994).

The basic understanding of the conceptual change process is that a student will typically first try to assimilate their prior conception with the new concept, allowing old ideas to adjust and meet the needs of the new concept. If the process of assimilation is unsuccessful, the student will then attempt to accommodate and replace the prior conception with the new concept (Posner et al., 1982). If the student is not satisfied with the results of assimilation or accommodation, the students will keep their existing conception, resulting in no conceptual change (Posner et al., 1982; Vosniadou, 1994). While the ideas of assimilation and accommodation explain how students are shifting their prior conceptions, it does not address why students decide to change their conception. Perhaps most importantly, the student must be dissatisfied with their current understanding of the concept for the process of conceptual change to even begin. This understanding has led to attempts to better explain and model conceptual change including the Conceptual Change Model (Posner et al., 1982) and the Cognitive Reconstruction of Knowledge Model (Dole & Sinatra, 1998) which will be explained in depth below.

Conceptual Change Model

Posner et al.'s (1982) Conceptual Change Model (CCM) was the first to build from Piaget's (1964) basic understanding of conception change to show the process a student undergoes when deciding whether or not to accommodate their prior conception. As shown in Figure 1, four conditions must be met for a student to decide to accommodate: (a) the student must have dissatisfaction with their prior conceptions and the student must find the new conception to be (b) intelligible, (c) plausible and (d) extendable (Posner et al., 1982). If any of the four conditions are not met, the student will keep their prior conception. Intelligibility means the student understands the terms, symbols and syntax used in the new conception, allowing them to create a representation of the concept. A conception is plausible if it (a) aligns with the student's fundamental assumptions, (b) is consistent with other knowledge and past experiences, (c) can be used to create an image of the conception, and (d) can be used to solve problems. An extendable concept allows for the student to further use and apply it. To be considered extendable, the student needs to be able to use the new conception to interpret new experiences and see future, fruitful potential (Posner et al., 1982).

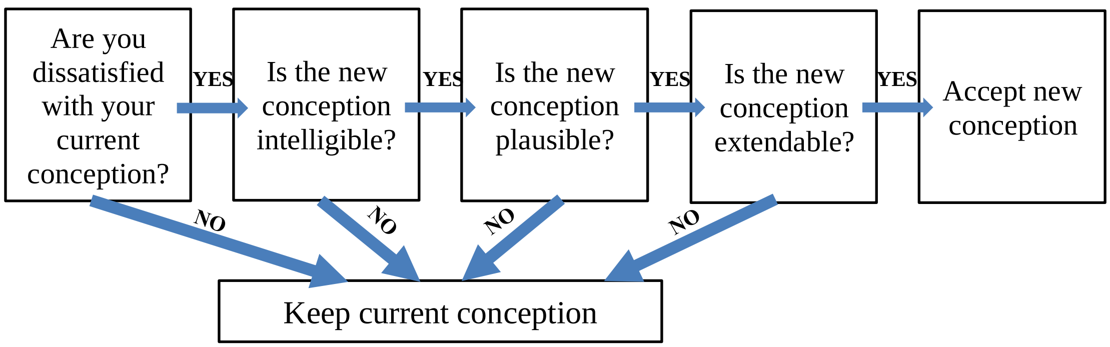


Figure 1.

Posner et al.'s (1982) Conceptual Change Model

In order to accept the new conception, the student must first be dissatisfied with their prior conception. The student must feel that their current conception does not help them understand and apply the new information. Commonly, this happens after the student attempts to assimilate their prior conception but cannot do so due to an anomaly. Anomalies occur when a student struggles to make sense of something while attempting to adapt the new conception to their prior conception. This anomaly creates dissatisfaction with the prior conception, creating the possibility the student will adopt the new conception. Once the student finds their prior conception dissatisfying, the student must find the new conception intelligible, plausible, and extendable. If the student finds the new concept intelligible, plausible, and extendable, the anomalies causing the initial issues with their prior conceptions should have been resolved (Posner et al., 1982).

While the CCM builds from the basic understanding of conceptual change to explain the necessary steps for a change to occur, it leaves some questions about the process students undertake when they are engaging in conceptual change. The CCM only allows for two options, conceptual change or no conceptual change, and does not account for the range of possible shifts in conceptual understanding that a student may experience. Conceptual change is a gradual process and may take many interactions with a phenomenon to fully occur, and not all students actually get to the point where there understanding fully aligns with that of the scientifically accepted conception (Vosniadou & Mason, 2012; Wade-Jaimes et al., 2018). Additionally, the CCM starts with a student being dissatisfied with their prior knowledge, but it does not explain what leads the students to be dissatisfied. Understanding how students evaluate their prior conceptions could lead to better models of instruction that encourage students' decision to engage in conceptual change.

Cognitive Reconstruction of Knowledge Model

The Cognitive Reconstruction of Knowledge Model (CRKM), developed by Dole and Sinatra (1998), builds from the CCM to show a more comprehensive model of conceptual change, expressing more of the complexities involved in the conceptual change process. As shown in Figure 2, the CRKM reorganizes the components of the CCM and adds the following constructs: (a) strength of the existing conception, (b) motivation, (c) peripheral cues and (d) engagement (Dole & Sinatra, 1998).

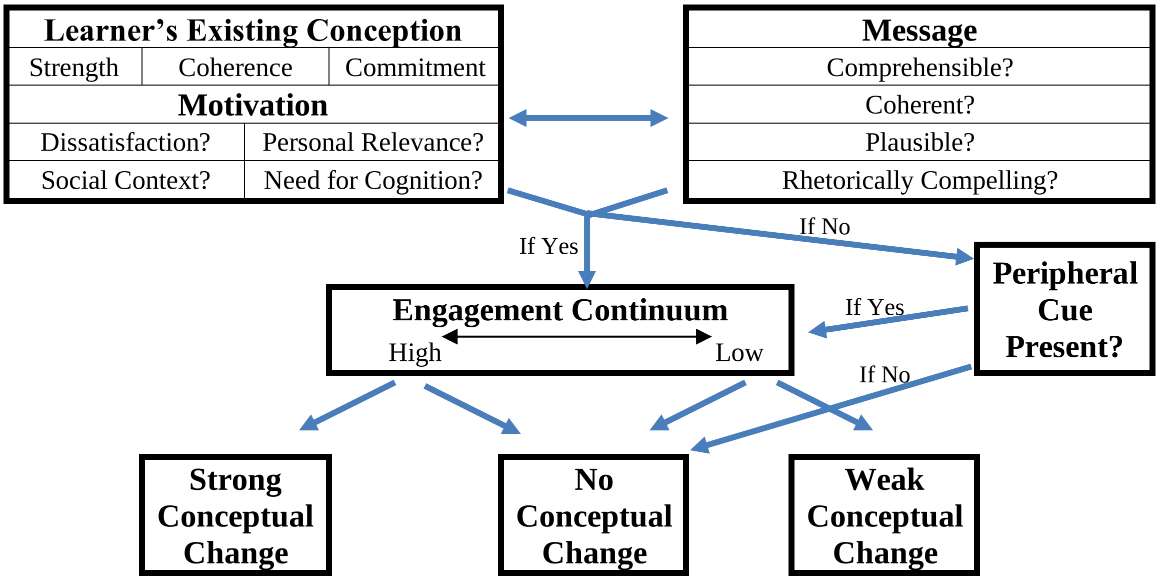


Figure 2.

Dole and Sinatra's (1998) Cognitive Reconstruction of Knowledge Model of conceptual change

The CRKM considers five major factors into a students' decision to engage in conceptual change: (a) learners existing conception, (b) motivation, (c) message, (d) engagement, and (e) peripheral cue. Learner's existing conception refers to the coherence of the students' prior conception. This takes into consideration whether the prior conception is detailed and well-structured or fragmented and lacking information. Learner's existing conception also makes allowances for how committed the student is to their prior concept. Students who are very committed to their conceptions are less likely to engage in conceptual change (Dole & Sinatra, 1998). These students are not willing to find dissatisfaction with their conception or are not willing to accept a different interpretation of the conception.

In the CRKM, the first step towards conceptual change occurs when a student is dissatisfied with their prior conception. The CRKM places dissatisfaction under the heading of motivation, along with other factors that may encourage or discourage a student to change their conception. The other factors within motivation include whether or not the conception is personally relevant to the student, if their peers are interested in the new concept, and finally if the student is willing to engage in the learning of the new concept (Dole & Sinatra, 1998). If a student is not motivated to change their conception for any of those reasons, conceptual change will not occur.

When a teacher is presenting new materials, some students choose to engage in conceptual change because of the strength of the teacher's argument or message (Dole & Sinatra, 1998). The teacher's message includes whether the student finds the new conception comprehensible, coherent, plausible, and rhetorically compelling. Some students are not motivated by the argument itself, but by the peripheral cues provided in the message. Peripheral cues are how attractive, trustworthy, credible, or easily understandable the students find the source of the information (Dole & Sinatra, 1998). When a student is not convinced by the message, peripheral cues provided by the teacher can convince students to engage in conceptual change.

When involved in a lesson, different students engage in the lesson at various levels. Engagement is the level at which students participate in processing, exercise reflection, and utilize strategies for learning (Dole & Sinatra, 1998). Low engagement tends to result in weak, or more likely no conceptual change. High engagement can result in strong conceptual change, but like low engagement, can also result in no conceptual change (Dole & Sinatra, 1998).

The CRKM model does not treat the resulting conceptual change as an all or nothing occurrence; instead, it recognizes that in addition to no conceptual change occurring, conceptual change happens on a spectrum from a weak conceptual change to a strong conceptual change. The CRKM also accounts for the fact that a strong conceptual change requires higher engagement from the student and weak conceptual change can be a result of low engagement (Dole & Sinatra, 1998).

The CRKM creates a more complete model of conceptual change, building from the original CCM. The CRKM model allows for a wider range of conceptual changes. Where the CCM only allowed for a change or no change (Posner et al., 1982), the CRKM characterizes the final change on a spectrum from a weak conceptual change to a strong conceptual change (Dole & Sinatra, 1998). The CRKM model also sets the groundwork for a larger discussion as to what factors play into a student deciding to change their current understanding of a concept. While both models emphasize that a student must be dissatisfied with their conception (Dole & Sinatra, 1998; Posner et al., 1982), the CRKM model uses aspects of the student's prior conception and the student's motivation to explain why a they decide to engage in a change (Dole & Sinatra, 1998). A final strength of the CRKM model over the CCM is that is accounts for the socio-cultural aspects of the classroom by including the social context, messaging, and peripheral cues (Dole & Sinatra, 1998). Social interactions are an important aspect of conceptual change

(Vosniadou & Mason, 2012). These factors combine to create a more detailed theoretical framework of conceptual change.

Further Research on the CRKM in Physics

Following the development of the CRKM, researchers used quantitative measures to further investigate the relationships between variables proposed in the original CRKM model as well as other factors that may be important to the conceptual change process in a physics classroom (Taasoobshirazi et al., 2016; Taasoobshirazi & Sinatra, 2011). As shown in Figure 3, the first study to empirically model the CRKM focused on how need for cognition and approach goal orientation influenced physics motivation which in turn influenced both conceptual change scores and course grade. Each of the constructs was evaluated using separate measures, and structural equation modeling was used to test the proposed relationships (Taasoobshirazi & Sinatra, 2011).

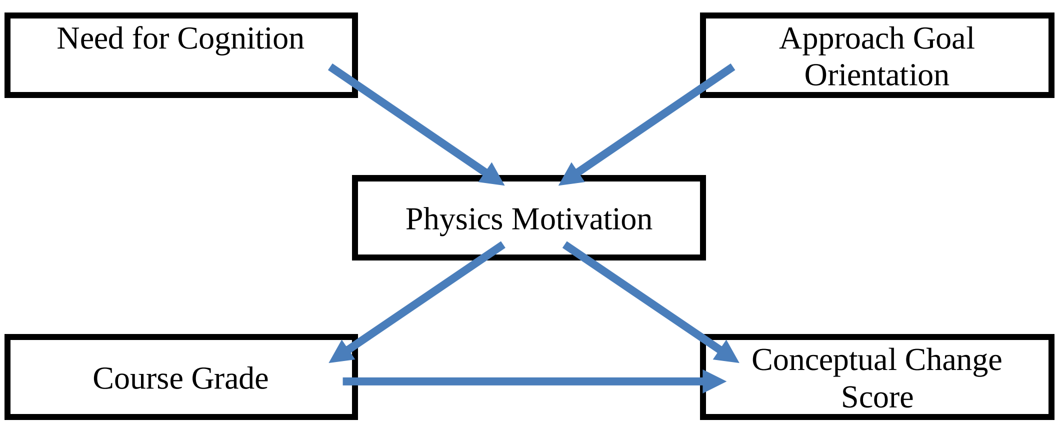


Figure 3.

Taasoobshirazi and Sinatra's (2011) model of factors leading to conceptual change in physics

For the purpose of Taasoobshirazi and Sinatra's (2011) study, need for cognition was defined as how often a student engaged in and enjoyed cognitive activities such as seeking out information or thinking about big ideas. Approach goal orientation was evaluated by whether a student had a mastery goal or a performance goal. A student with a mastery goal is focused on learning and understanding the concept being taught as opposed to a student with a performance goal who is focused on their score on the assessment or how competent they appear to others. Motivation was a multidimensional construct that included intrinsic motivation, extrinsic motivation, task relevancy, self-determination, self-efficacy, and assessment anxiety. Intrinsic motivation is motivation from within the student such as doing an activity due to interest while extrinsic motivation is from outside sources, such as doing an activity to get a good grade. Task relevancy is how relevant an activity is to a student's goals. Self-determination refers to how much choice and control a student has over their own learning. Self-efficacy is the student's beliefs in their own capabilities. And assessment anxiety is the level of anxiety a student has about an assessment including how it effects their performance. The results of the analysis showed that need for cognition and approach goal orientation correlated highly with physics motivation. Despite finding high correlations, researchers felt there were variables missing from the model (Taasoobshirazi & Sinatra, 2011).

Based from the recommendations of that study, a second study was conducted to include achievement emotions such as enjoyment, boredom and anxiety as well as deep cognitive engagement in the previous model of conceptual change in physics (see Figure 4). Enjoyment is a positive emotion that had been shown to have a positive link with mastery goals and motivation. Boredom and anxiety are negative emotions that tend to deter focus from the task at hand (Taasoobshirazi et al., 2016). Just as it is defined in the CRKM, engagement is how the students involve processing, reflection, and strategies in their learning (Dole & Sinatra, 1998; Taasoobshirazi et al., 2016).

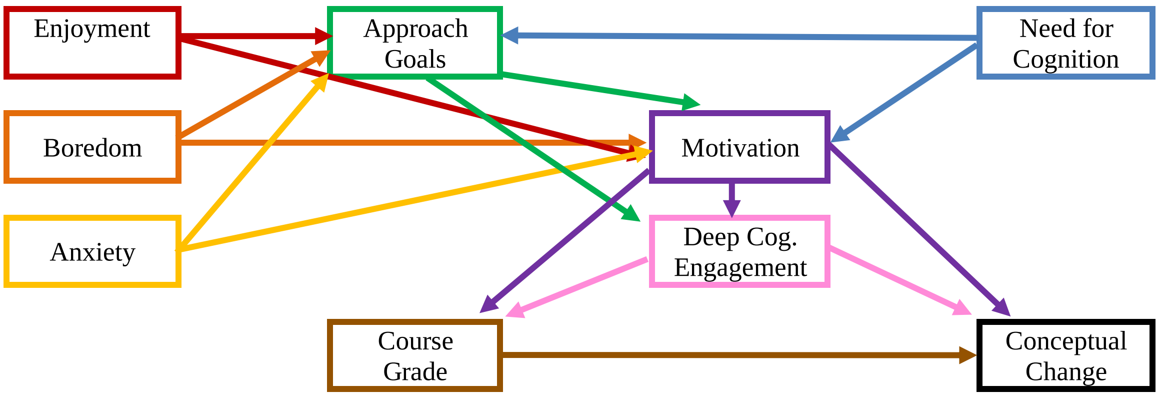


Figure 4.

The original conceptual change model tested by Taasoobshirazi et al. (2016)

An initial analysis found that boredom, anxiety and need for cognition did not play a significant role in the CRKM model. Once those constructs were removed, a new model (see Figure 5) was developed that included (a) enjoyment, (b) approach goal orientation, (c) motivation, (d) deep cognitive engagement, (e) course grade and (f) conceptual change. This updated version showed a strong relationship between the variables (Taasoobshirazi et al., 2016). Again, researchers recommend that new variables, such as learner and contextual variables, should be tested with the CRKM to better understand which variables have the most impact in creating conceptual change in physics.

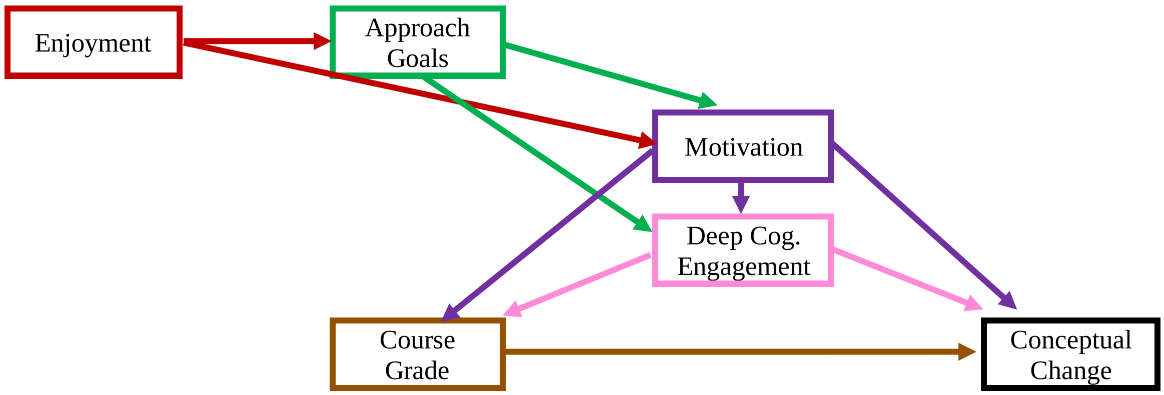


Figure 5.

Taasoobshirazi et al.'s (2016) revised conceptual change model

A separate study considered how different levels of student engagement and goal orientation affects the conceptual change process (Ranellucci et al., 2013). Deep processing involves extension, elaboration, and critical thinking, while shallow processing is memorizing and reproducing content. Unlike shallow, deep processing resulted in larger conceptual change and was also tied to students with mastery-approach goals. Mastery approach goals are goals focused on understanding and learning, as opposed to performance-approach goals which are goals focused on ability and competence. The study also found that students with higher levels of prior knowledge that align with the scientifically accepted knowledge are more likely to experience conceptual change (Ranellucci et al., 2013). This reinforced the CRKM approach by further explaining factors that affect the students' motivation and emphasizing the importance of student engagement in conceptual change.

Dynamic Model of Conceptual Change

With the additional research on variables the CRKM included as factors in a student's decision to engage in conceptual change, there was a need for an updated model. The Dynamic Model of Conceptual Change (DMCC) was developed to emphasize the non-linear nature of conceptual change while more clearly demonstrating how different variables play into a student's decision to engage in conceptual change (Nadelson et al., 2018). The DMCC (Figure 6) builds from the CCM and the CRKM to demonstrate the variety of paths students take while engaging in the conceptual change process as well as more clearly defining the spectrum of conceptual change outcomes. There are four stages in the DMCC: (a) message, (b) message consideration, (c) engagement in processing, (d) conceptual change (Nadelson et al., 2018).

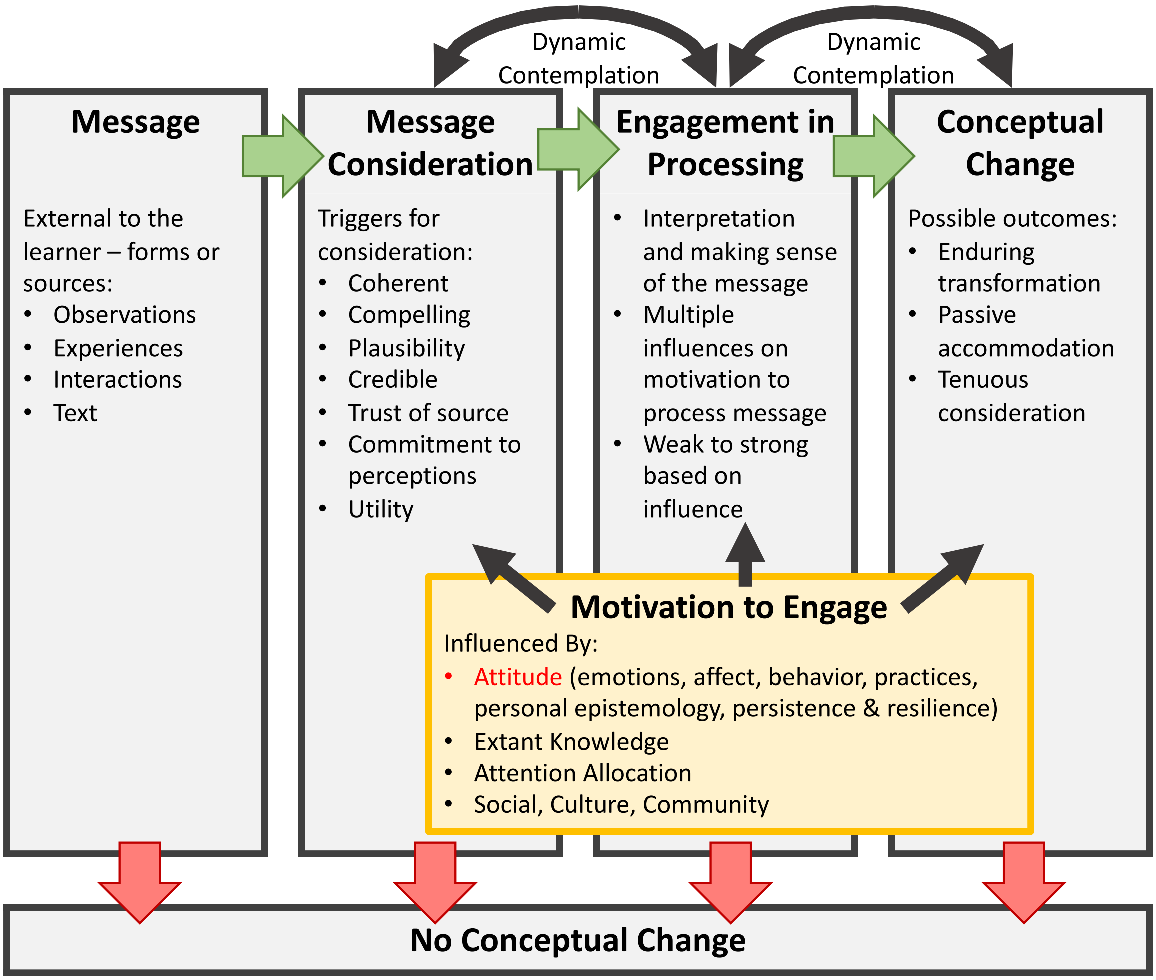


Figure 6.

Nadelson et al.'s (2018) Dynamic Model of Conceptual Change

The first step in the DMCC is the message (Nadelson et al., 2018). At this point, the student is only being exposed to the external message, they are not engaging with the information yet. The message can come from text, observations, interactions, or experiences. After experiencing the message, the student can either move on to step two or ignore the message, which results in no conceptual change (Nadelson et al., 2018).

In the second step, the student recognizes and considers the message. This is when the student considers the content, source, credibility, coherency, and plausibility of the message. Like step one, the student has two options after recognizing and considering the message: they can either move on to step three or ignore the message, which results in no conceptual change (Nadelson et al., 2018).

After recognizing and considering the message, the student can move to the third step in which they engage in message processing, contemplations, and sense making. Engagement can be cognitive, affective, and/or behavioral. A wide assortment of personal and external variables can impact what a student does with step three. The student has three options from step three. They can either move on to step four, loop back to step two, or ignore the message which results in no conceptual change (Nadelson et al., 2018).

The final step is conceptual change, explained by a spectrum of possible outcomes. At one end of the conceptual change spectrum is enduring transformation. Enduring transformation occurs when a student understand, accepts, and actively commits to the new concept. Passive accommodation occurs when a student accepts and commits to the new concept, but there is no notable change in behavior. Tenuous consideration occurs when a student understands the new concept but does not fully accept the concept or does not fully commit to it. And at the opposite end of the spectrum is no conceptual change. This happens when the student understands the new concept but does not accept or commit to it. This results in the student retaining their prior conception. After engaging in step four, the student can loop back and repeat step three (Nadelson et al., 2018).

Motivation to engage is an important factor in how students interact with the message in steps two through four (Nadelson et al., 2018). Motivation is defined as the determination to engage in the conceptual change process. Engagement can be cognitive, affective, and/or behavioral. Cognitive engagement occurs when students interact, process, or make sense of information. Affective engagement is the level of emotion response from interacting with the concept and the feeling of involvement with the concept. Behavioral engagement is actions such as attention, persistence, knowledge seeking, and self-regulation. (Nadelson et al., 2018). Motivation to engage plays into how students interact with the concept at hand.

Motivation to engage is influenced by an array of variables such as (a) attitude, (b) extant knowledge, (c) attention allocation, and (d) social, culture and community factors. (Nadelson et al., 2018). Attitudes are defined as the evaluation of a topic concept that led to the liking or disliking that topic. Extant knowledge is the prior knowledge the students uses to interpret the concepts. Attention allocation is important because students who allot more attention to a message are more likely to engage in conceptual change. Social, cultural and community factors that may be considered when engaging in the process of conceptual change include the influence of family, teachers, peers, community, organizations, neighbors and media (Nadelson et al., 2018). All of these variables, (a) attitude, (b) extant knowledge, (c) attention allocation, and (d) social, culture and community factors, influence the student's motivation to engage which influences the student's success in the conceptual change process.

The DMCC improves upon the CRKM in that it introduces the dynamic, non-linear aspect of conceptual change with the multiple paths, loops, and exit points for students to take during the process (Nadelson et al., 2018). While the CRKM explains multiple connections between variables and the conceptual change process, it is still a linear model of conceptual change (Dole & Sinatra, 1998). The DMCC approach demonstrates that there are multiple points along the conceptual change process where a student may disengage (Nadelson et al., 2018), while the CRKM does not give a path for students to end the conceptual change process early (Dole & Sinatra, 1998). Additionally, the DMCC introduces variables that show the messy interaction between the conceptual change process, motivation to engage, and an array of variables that influence the student's ability to engage. This is the first model to take a socio-culture lens to conceptual change. (Nadelson et al., 2018). While the DMCC includes prior (extant) knowledge in their model, it does not address the student's dissatisfaction with their prior knowledge as a motivation to start the process of conceptual change. The DMCC views conceptual change as the process of a student adding a new schema to their library rather than replacing or adapting a prior schema. As a result of the conceptual change process, the student may choose which schema they will use more or less (Nadelson et al., 2018). The DMCC does not address how the students judges their prior knowledge or decides which schema to use.

Regardless of the context of a student's prior knowledge and their level of engagement in the lesson, in order for a student to start the process of conceptual change, the student must first and foremost be dissatisfied with their prior conception (Dole & Sinatra, 1998; Posner et al., 1982). To do so, a student must be aware of their own beliefs, understandings, and other cognitive enterprises, also known as metacognition (Flavell, 1979). If a student reaches an anomaly in their cognition, a metacognitive experience should flag the need to critically analyze their conception (Flavell, 1987). Metacognitive experiences encourage conceptual change in that they "can affect your metacognitive knowledge base by adding to it, deleting from it, or revising it" (Flavell, 1979, p. 908).

Some research has started to address metacognition as an element of the conceptual change process. When measuring depth of processing, Ranellucci et al. (2013) coded for metacognitive comments made by the students during a think aloud. A think aloud is a data collection technique in which researchers ask participants to talk through their thought processes while completing a task, such as solving a physics problem (Ericsson & Simon, 1993; van Someren et al., 1994). The use of metacognitive comments was used to judge the level of engagement a student had with the new material, not necessarily how a student was using metacognition to address their prior conceptions. Their recommendations were that future research clearly define and separate depth of processing and cognitive engagement when investigating conceptual change (Ranellucci et al., 2013). Heddy et al. (2018) distinguish metacognition from engagement in that engagement is focusing on the characteristics of the message such as credibility and coherency while metacognition focuses on the students' knowledge and learning processes.

The different models of conceptual change help to explain the process a student undergoes when shifting their conception of a physics concept once the students decides they are dissatisfied with their current understanding (Dole & Sinatra, 1998; Posner et al., 1982; Ranellucci et al., 2013; Taasoobshirazi et al., 2016; Taasoobshirazi & Sinatra, 2011). The models do not explain how a student evaluates their prior conception to decide if they are dissatisfied. Metacognition, particularly comprehension monitoring, is part of the conceptual change process (Hewson, 1992), therefore, assessing students' judgments of their understandings through metacognitive insights may provide a better measure of conceptual change than knowledge tests alone (Gunstone et al., 1992). Stronger conceptual change can happen when a student engages in metacognitive awareness (Gunstone et al., 1992). This missing part of the conceptual change models creates to a desire to better understand how students engage with and assess their own cognition during the process of conceptual change. In other words, how do students engage in metacognition in order to initiate the conceptual change process.

Metacognition

Flavell defined metacognition as "knowledge and cognition about cognitive phenomena" (1979, p. 906). Metacognition is different from cognition. "Metacognitions are second-order cognitions: thoughts about thoughts, knowledge about knowledge, or reflections about actions" (Weinert, 1987, p. 8). Cognition consists of the skills and knowledge that are needed to perform a task, while metacognition is the understanding of how well the task was performed (Schraw, 1998). For the purpose of this study, cogntion will be measured with a problem solving framework. For example, if a student is working on a physics problem, cognition involves reading the problem while metacognition occurs when a student assesses if they understand the problem as shown in Table 1. Cognitive skills tend to be more content specific while metacognitive skills tend to be more general and span multiple content areas (Schraw, 1998). Although different, cognition and metacognition are closely related and can be difficult to distinguish due to the fact that they depend on one another, creating a circular relationship (Veenman et al., 2006).

Table 1

Examples of How a Student May Use Cognition and Metacognition While Solving a Physics Problem

Cognition	**Metacognition**
Reading the problem	Assessing their understanding of the problem
Pulling key information from problem	Evaluating which problem solving strategy would be optimal
Calculating and choosing appropriate units	Assessing the appropriateness of the magnitude of the numbers

Metacognition has two distinct components, knowledge of cognition and regulation of cognition (Schraw, 1998; Schraw & Dennison, 1994; Taasoobshirazi & Farley, 2013). The two components of metacognition further break down into eight subcomponents as shown in Figure 7. Knowledge of cognition includes declarative knowledge, procedural knowledge and conditional knowledge. Regulation of cognition includes planning, information management, comprehension monitoring, debugging, and evaluation (Schraw, 1998; Schraw & Dennison, 1994; Taasoobshirazi & Farley, 2013). Knowledge of cognition, regulation of cognition, and their respective subcomponents will be explained in detail below.

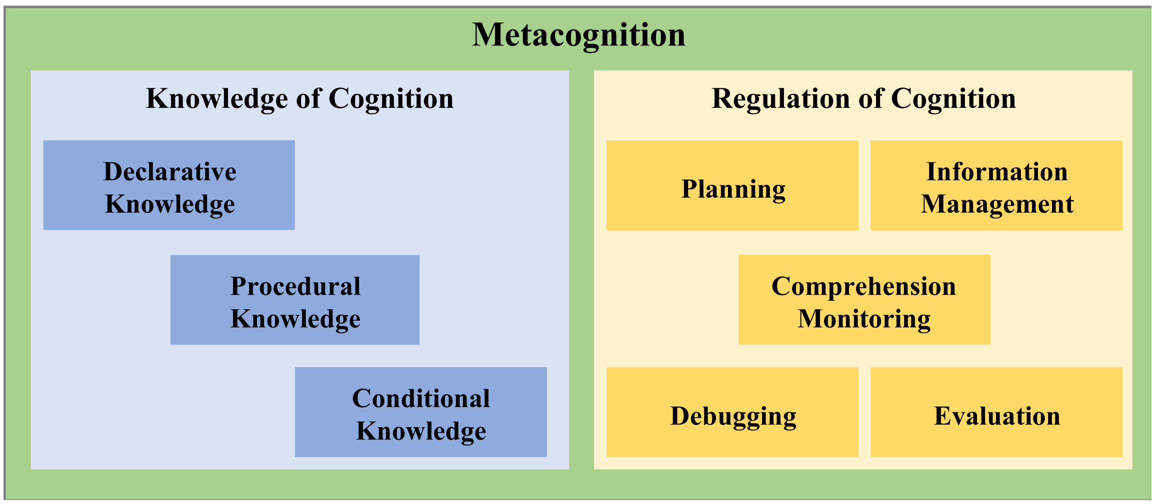


Figure 7.

Two components and eight sub-components of metacognition (Schraw, 1998; Schraw & Dennison, 1994; Taasoobshirazi & Farley, 2013)

Knowledge of Cognition

Knowledge of cognition refers to what a student knows about cognition in general and more importantly about their own cognition. There are three types of knowledge of cognition: (a) declarative, (b) procedural, and (c) conditional (Schraw, 1998; Schraw & Dennison, 1994; Taasoobshirazi & Farley, 2013). In the metacognitive model, declarative knowledge is the knowledge a student has about themselves as a learner, and what strategies and conditions impact their performance. For example, a student may think they are good at mathematics but struggle with writing. Procedural knowledge, in the metacognitive model, refers to knowledge a student has about how to do a task. This may include a student knowing how to apply a problem-solving strategy. And finally, conditional knowledge is the understanding a student has about when and why to use declarative and procedural knowledge. In physics, an example of this would be a student knowing when to use Newton's Laws as opposed to conservation laws to solve a problem. The conditional knowledge is applied when the student decides to use a Newton's Law approach rather than a conservation laws approach to the problem. The procedural knowledge is applied when the student applies Newtons' Laws problem solving strategies in order to solve the problem (Schraw, 1998; Taasoobshirazi & Farley, 2013). Knowledge of cognition allows a student to gauge their learning, but it does not help them to organize and check their learning.

Regulation of Cognition

Regulation of cognition is a student's ability to control and monitor their learning. Within regulation of cognition, there are five subprocesses: (a) planning, (b) information management, (c) comprehension monitoring, (d) debugging, and (e) evaluation (Schraw, 1998; Schraw & Dennison, 1994; Taasoobshirazi & Farley, 2013). Planning involves selecting strategies, allocating resources, and setting goals prior to working in a task. A student working on a lab may decide what materials they need before starting the lab (Schraw, 1998; Taasoobshirazi & Farley, 2013). Information management are strategies that help students be more effective. In physics, an information management strategy is to draw and label a picture or diagram before starting to solve a problem (Taasoobshirazi & Farley, 2013). Comprehension monitoring refers to a student's real time assessing of their progress, comprehension, and goals. While problem solving, a student may check their work every few steps to make sure they have not made any mistakes (Schraw, 1998; Taasoobshirazi & Farley, 2013). Debugging involves using strategies to fix errors and alter learning. Debugging can be as simple as a student seeking help when they do not fully understand a concept (Taasoobshirazi & Farley, 2013). And finally evaluation is the process that occurs when the student evaluates their work or product once it is completed. For example, when a student is done with a problem, they may judge how correct their answer is (Schraw, 1998; Taasoobshirazi & Farley, 2013).

Metacognitive Development

Metacognitive skills continue to grow and develop with age (Kuhn, 2000; Veenman & Spaans, 2005; Veenman et al., 2004). The first awareness of metacognitive abilities begins in children around ages three to five (Dimmitt & McCormick, 2012; Veenman et al., 2006). At this stage, children have theory of mind, or an ability to understand and attribute mental states to themselves and others. In doing so, they are able to start to distinguish reality from false beliefs (Dimmitt & McCormick, 2012). By age 11 or 12, children begin to develop and apply metacognitive knowledge and skills. (Veenman & Spaans, 2005). By high school, when most students first formally encounter physics, students are able to engage in a variety of metacognitive strategies and apply these strategies to different contexts (Dimmitt & McCormick, 2012). Not only are high school students able to use multiple metacognitive strategies, they are also able to evaluate the effectiveness of those strategies and switch to other, more effective, strategies if needed (Dimmitt & McCormick, 2012). Students are more likely to engage in metacognitive strategies if those strategies are directly taught (Dimmitt & McCormick, 2012). Additionally, metacognitive skills are highly interdependent, so developing one skill often leads to developing another (Veenman & Spaans, 2005). For example, a student who is good at planning tends to also be good at monitoring during the problem solving process, and evaluation once the problem is complete.

Not only does metacognitive ability depend on age; it is also found to be correlated with intelligence (Veenman & Spaans, 2005; Veenman et al., 2006; Veenman et al., 2004). Intelligence is defined as to the magnitude and quality of cognitive knowledge and skills (Veenman & Spaans, 2005). Highly intelligent students tend to exhibit more metacognitive activities (Veenman & Spaans, 2005). Intelligence and metacognitive knowledge develop in a parallel path (Veenman & Spaans, 2005) where intellectual ability mediates the development of metacognitive skills (Veenman et al., 2004). Additionally, it was found that both metacognition and intelligence individually and collectively accounted for the variance in mathematics performance for secondary students (Veenman & Spaans, 2005).

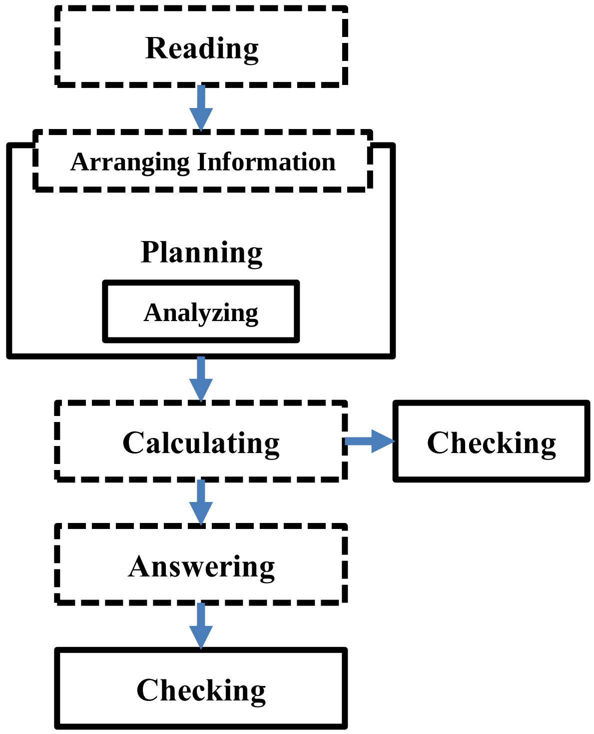
Metacognition in Physics

Some research has explored how metacognition is used in high school and college physics classes as well as the effect of metacognition on student learning. One such study investigated how metacognitive tools support conceptual change (Wade-Jaimes et al., 2018). Throughout a physics unit on circuits, a class of high school students was offered multiple experiences and resources to conceptually engage with their circuits content knowledge. This variety of representations provided students multiple opportunities to make connections between their mental models of circuits and the scientifically accepted physics conception, with the hopes of creating a discrepant event that could start the process of conceptual change. Some students in the study were able to demonstrate a correct explanation of a concept, but still needed more time to resolve uneasiness with the more abstract aspects of the concept. Teacher questioning and probing of students was found to be key in getting students to use metacognition. This is because students did not always use a specific metacognitive tool as the teacher intended (Wade-Jaimes et al., 2018). A student may simply use a tool because a teacher asked them to use it, but they may not use the tool in a way to seek deeper meaning or understanding. Students may need help and additional prompting to use metacognition effectively while learning physics.

College students enrolled in an introductory physics class were asked to use a physics tutorial. In the tutorial, students were asked to solve a set of physics problems and watch a video of an expert's explanation of the answer. Students were also asked to answer a set of metacognitive prompts that were gradually scaffolded away (Osman, 2010). As a result of the tutorial, students showed an increase in their mean metacognitive awareness test score. Students commented that they became more aware of their thinking process, planning strategies, and their ability to check for accuracy. The researcher suggested that metacognition about problem solving strategies may be more important than the problem solving strategies themselves when nurturing students' physics knowledge (Osman, 2010). Many students can use a problem solving strategy to reach the correct answer, but still not understand the underlying physic concept of the problem. The metacognitive strategies, more so than the problem solving strategies, raise the student's awareness of their ongoing thought processes and check for accuracy (Osman, 2010). This may help in achieving a greater understanding of the underlying concept itself.

A second study also used prompts to help high school students enrolled in introductory physics to plan, monitor, and judge their own work (Jax et al., 2019). This specific study was investigating the use of contrasting cases in the prompts during a physics circuit simulation. Contrasting cases show students a good example as well as a bad example of the problem solving and circuit building the students were learning in the simulation. Prior research noted that when students have a range of examples to compare, they notice more features within the examples. The results indicated that students who were exposed to the contrasting cases, rather than just the good examples, were more accurate at assessing their own performance and demonstrated a higher performance on their final assessment (Jax et al., 2019). The use of contrasting cases could help increase students' metacognitive awareness by making students aware of good and bad examples of work, allowing them to compare their work to those examples, gauge their understanding, and evaluate their cognition.

Phang (2009) used grounded theory to develop a model of how secondary students solve physics problems and where metacognition fits into the problem solving process. As shown in Figure 8, students typically follow a path that begins by reading the problem. After the student reads the problem, they tend to plan their strategy for solving the problem by arranging information and analyzing the problem. The next step in problem solving is to perform the calculation. Occasionally, students will pause during the calculation step to check their work. Following the calculation, students will answer the question. The last possible step in a typical problem solving session is to check the answer. While this is a typical path, students can skip steps, repeat steps, or loop back to an earlier step based on their understanding of the problem (Phang, 2009, 2010). A second study conducted using a second sample confirmed the model (Phang, 2010).



Note: Solid boxes indicate metacognitive processes while dashed boxes represent cognitive processes.

Figure 8.

Phang's (2009, 2010) pattern of physics problem solving

Some of the steps in this physics problem solving model represent cognitive knowledge and others metacognitive knowledge. As demonstrated with the dashed boxes in Figure 8, reading the problem, arranging information, calculating, and answering the question are all typically cognitive processes. Phang (2009, 2010) identified that the metacognitive processes, as shown in the solid boxes in Figure 8, are the planning, analyzing, and checking steps while problem solving. Different students employ different strategies while problem solving, changing the amount of cognitive versus metacognitive knowledge the student uses. For instance, if a student does not check their work at any step during the problem solving process, they decrease their opportunities to use metacognition (Phang, 2009, 2010). Additionally, students may choose to use a metacongtive strategy while engaged in a cognitive problem solving processes. For example, a student may monitor their comprehension while reading the problem (Phang, 2009). This model shows the typical places in problem solving where students implement metacognition, if they are engaging in metacognitive processes.

Simulations are frequently used to help students visualize and more easily manipulate physics concepts in an attempt to address misconceptions. Moser et al. (2017) used prompts in a conservation of energy simulation in physics lesson for secondary students to see if a combination of metacognitive training and metacognitive prompts would promote better performance from students on an assessment of knowledge on conservation of energy. At first glance, the data showed no statistically significant difference between the four cases: (a) no prompting or training, (b) prompting but no training, (c) training but no prompting, and (d) training and prompting. The only significant predictor of the students' posttest knowledge of energy score was prior knowledge as assessed on the pretest. Researchers went back through their data and coded not only if the students were provided a metacognitive prompt, but also how the student used the prompt. During the second analysis, researchers found that students who more effectively and intensely applied the metacognitive prompts scored higher on the posttest with a statistically significant difference as compared to students who did not apply the prompts. Students who purposively used the prompts by taking notes and repeatedly using the strategies were those who gained the most benefit from the metacognitive prompts. The effectiveness of the supports provided in the simulation depended on how the student used those supports (Moser et al., 2017). This demonstrates the importance of not only understanding if a student in using metacognitive learning strategies, but also how the student is using the strategy.

A similar finding was found when analyzing the metacognition of university physics students in a laboratory setting (Kung & Linder, 2007). Researchers coded student conversations during a laboratory activity for (a) comments that were metacognitive in nature, (b) statements that were part of the logistics of the lab, and (c) statements that were off task. Comments were analyzed by looking at the quantity of metacognitive statements as well as the time during the lab when the comments were made. Researchers concluded that it did not matter how many metacognitive statements were made, nor when they occurred in the lab. What was more important is what the students did following the metacognitive statement. If a student made a metacognitive statement, such as a statement that expressed a misunderstanding, but neither the student nor their lab partners worked to clarify the misunderstanding, the metacognitive statement did not seem to impact the students' learning. If instead that same metacognitive statement resulted in the group of students trying to make sense of the misunderstanding, the metacognitive statement proved to be more fruitful (Kung & Linder, 2007). The usefulness of metacognition in physics is not in whether it is used, but how it is used. For a student to change their understanding and start the process of conceptual change, a student not only has to be metacognitive and assess their understanding, but they must also act on the misunderstanding and try to understand why they do not understand.

Measures of Metacognition in Physics

Overall, there has been little research within physics research examining the use of metacognition specifically in problem solving (Phang, 2009; Taasoobshirazi & Farley, 2013). Taasoobshirazi and Farley (2013) developed the Physics Metacognition Inventory to provide researchers with a tool to assess physics student's metacognition during problem solving and open new opportunities for research. The Physics Metacognition Inventory is a 26-item self-report survey that uses a five-point Likert-type scale which aligns with the conception of metacognition. The 26 items load into six factors: (a) knowledge of cognition: declarative, procedural, and conditional, (b) regulation of cognition: information management, (c) regulation of cognition: monitoring, (d) evaluating, (e) regulation of cognition: debugging, and (f) regulation of cognition: planning (Taasoobshirazi et al., 2015). Exploratory factor analysis, confirmatory factor analysis, and Rasch analysis were used to confirm the overall reliability and construct validity of the Physics Metacognition Inventory (Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013). The Physics Metacognitive Inventory item reliability was 0.97 (excellent) and the person reliability was 0.86 (good) (Taasoobshirazi et al., 2015). The Physics Metacognition Inventory will allow future research to quantitatively asses the impacts of metacognition on physics problem solving.

Mota et al. (2019) found that using a combination of prompting and collaboration while solving physics problems helps students increase their use of metacognition. In their study, college students were given a set of physics problems to work on alone, prior to their class. Once in class, the students spent 45 minutes discussing their solutions with a peer group followed by another 45 minutes working with their group to compare their work to the correct solutions that were provided by the teacher. At the end of the class session, students were asked to complete a reflection form. The student reflections were coded based on coding categories created from the Physics Metacognitive Inventory. Results showed that in the reflections, students made more comments coded as knowledge of cognition categories as compared to regulation of cognition, with the most comments coded as declarative knowledge. The study found that this approach to physics homework problems improved the students' use of metacognition over time. Additionally, students could more accurately rate their understanding as the semester went on (Mota et al., 2019). This study demonstrates how, with the supports in place, physics practice problems can be used to increase and enhance reflection and metacognition. One limitation of this study is that it looked at how students reflected and used metacognition after working on, explaining, and evaluating their work, not while they were actively solving the problems.

By better understanding how students use metacognition while solving physics problems, we can gain a perspective as to how students are engaging in conceptual change while solving problems. To start the process of conceptual change, a student first needs to be dissatisfied with their current understanding of a physics concept (Posner et al., 1982). To find the understanding dissatisfying, the student needs to monitor, reflect on, and evaluate their current understanding. These are all metacognitive processes, specifically regulation of cognition processes (Schraw, 1998; Schraw & Dennison, 1994; Taasoobshirazi & Farley, 2013). The process of conceptual change begins with metacognition.

Future Research

As Hammer et al. (2005) concluded their book chapter, if physics education research is going to focus on long term learning and not just short term fixes, "we must take into account the metacognition/epistemology literature… and the importance of helping students become deliberative and reflective about their own learning processes" (p. 23). It is not just content knowledge and problem solving skills that are important for solving physics problems, but also reasoning and metacognition (Mason & Singh, 2011). Students who use metacognition tend to have fewer erroneous conceptions and mental models (Rozencwajg, 2003). But research has shown that it is not enough for students to engage in metacognitive strategies, it is more important to understand how and when students engage with their metacognitive knowledge (Kung & Linder, 2007; Moser et al., 2017; Osman, 2010). Further, Sinatra and Taasoobshirazi (2018) shared a need for research to further explore how the different processes of metacognition contribute to problem solving success. More research is needed to better understand how, when, and why students use metacognition (Dimmit & McCormick, 2012) especially in regard to their decision to undergo the conceptual change process. Specifically, how is metacognition used by students to evaluate their prior knowledge to decide if they are satisfied or dissatisfied with their prior conception.

My focus is specifically how students use metacognition during problem solving in physics. Physics problems, particularly higher order thinking problems, tend to encourage the use metacognitive strategies (Abdullah et al., 2013). In a traditional physics classroom, problem solving is a main focus and teaching tool (Kim & Pak, 2002; Mulhall & Gunstone, 2012). My overall research goal is to better understand how students use metacognition in problem solving. The research questions for the study were:

1. How do current high school physics students use cognition and metacognition to solve physics problems?
2. In what ways do current high school physics students voice dissatisfaction with their content knowledge while solving a physics problem, and does that dissatisfaction lead to conceptual change?

Chapter Three

Methods

This study employed a concurrent, complementary, explanatory mixed method design with qualitative priority (Creamer, 2018; Greene et al., 1989). The study occurred in three portions, a quantitative portion, a qualitative portion, and a mixed analysis portion. A snowball sample was used to explore how high school physics students use metacognition while solving physics problems.

Due to changes in the educational environments and physical distancing restrictions brought on by the coronavirus disease 2019 (COVID-19), the timing and scope of the study was adjusted from the original dissertation proposal. The original study was designed to be conducted in a public high school with the collaboration of high school physics teachers in the fall of 2020. A large sample of high school students taking their first year of Algebra I based physics was going to be assessed on both their current level of physics content knowledge using the Force Concept Inventory (Hestenes et al., 1992) and physics metacognitive strategy use using the Physics Metacognitive Inventory (Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013). Using the results of the quantitative analysis from the larger sample, a nested sample would have been purposely selected based on level of physics content knowledge and metacognitive strategy use. These participants would have been invited to participate in the qualitative phase to further investigate student use of metacognition while solving physics problems using in person think aloud interviews.

The entire study was moved to a virtual platform using Webex because of physical distancing guidelines and most school districts moving to virtual schooling due to COVID-19. The study was conducted in the summer of 2020 and used a convenience sample of high school students who had just completed their first year of Algebra I based physics. The content of the problems used in the think aloud (kinematics, forces, and circular motion) are typically covered in the beginning of the school year. This allowed me to work with participants who had learned that content in a traditional, face to face high school physics class, prior to schools shifting to a virtual school model in the Spring of 2020.

Because of the virtual nature of the revised study, I could not monitor the participants while they took the Force Concept Inventory (Hestenes et al., 1992). This meant that I could not ensure that the participants did not seek help when answering questions. If the participants did seek help, the results of the Force Concept Inventory would no longer represent their current level of physics content knowledge. Additionally, the terms for using the Force Concept Inventory included the requirement that participants be supervised at all times during the administration of the assessment to ensure the security and validity of the measure. For these reasons, the Force Concept Inventory was not used to measure the participants' level of physics content knowledge.

For the revised mixed methods study, integration occurred at the research question, unit of analysis, sample, data collection, and analytics parts of the study as shown in Table 2 (Tashakkori & Teddlie, 2003; Yin, 2006). Since there was a mixed and a qualitative research question, integration happened at the research question level. To ensure integration within the unit of analysis and data collection, both quantitative and qualitative measures were used concurrently to assess metacognitive use while solving physics problems in order to answer the two research questions. All participants completed the quantitative and qualitative portions of the study, creating sample integration. And finally, integration occurred at the analytic level because the quantitative and qualitative data were analyzed separately, and then combined to compare what metacognitive strategies students reported using and actually used during the think aloud.

Table 2

Visual Explanation of Mixed Methods Integration

Integration Location	**Explanation of Integration**
Research Question	The study had one mixed and one qualitative research question
Unit of Analysis	All portions of the study were measured per participant metacognitive use while solving physics problems.
Sample	All participants participated in both the quantitative and qualitative data collection
Data Collection	Data collection was concurrent, quant→QUAL
Analysis	The quantitative and qualitative data were analyzed both separately and in an integrated way.

Table 3 shows a visual breakdown of steps used in the mixed-methods research design. Following Avargil et al.’s (2018) recommendation to use both quantitative and qualitative methods to measure metacognition, individual physics students’ use of metacognition while solving physics problems was measured by using the Physics Metacognitive Inventory and a think aloud procedure. By using these two complementary approaches, the more detailed results from think aloud enhanced the results of the Physics Metacognitive Inventory (PMI; Creamer, 2018; Greene et al., 1989). While the PMI can show researchers what metacognitive tools are being used, the think aloud can further explain when and how metacognitive tools are being used. Additionally, since both the PMI and think aloud measured the similar metacognitive processes, it reduced potential threats to validity through triangulation.

Table 3

Visual Representation of Mixed-Methods Design Procedure (adapted from Gasiewski et al., 2012)

Portion	Procedure	Product
QUANTITATIVE Data Collection	• Demographic questionnaire • Physics Metacognition Inventory (PMI)	• Quantitative data
QUALITATIVE Data Collection	• Think aloud protocol while solving 3 physics problems	• Audio and video of think aloud • Transcriptions of think aloud • Participant work samples
QUANTITATIVE Analysis	• Descriptive analysis	• Descriptive summaries of demographic and PMI data
QUALITATIVE Analysis	• Coding and thematic analysis for metacognition, problem solving steps and emerging codes	• Coded transcriptions • Answer research questions
INTEGRATION Quantitative & Qualitative Results	• Cross validation of findings • Qualitative themes compared to quantitative results	• Answer research questions • Discussion • Implications • Conclusions

Participants

The population of interest was high school physics students who had just completed their first Algebra I based physics class. Physics, Honors Physics, and AP Physics 1 are common Algebra 1 based physics options for high school students. It is possible that some students enrolled in AP Physics 1 could be taking the course as a second-year physics student and could bias the sample. Second-year physics students would possibly have more physics content knowledge and longer exposure to physics metacognitive processes as compared to the first-year physics students. As a result, only first-year high school physics students were recruited for the study.

A recruitment email was sent to personal contacts who may know potential participants. A snowball approach was used, encouraging those email recipients to share the information with other possible participants. Once a physics student agreed to participate in the study, email correspondence was used to schedule a date and time for the virtual interview. Before participants were able to start the virtual interview, a parent or guardian signed an online consent form and the participant signed an online assent form. Each participant was assigned a pseudonym to keep identities anonymous.

As a result of the recruitment, 10 students were identified as potential participants and were emailed directly with more information about participating. Seven high school students who had finished their first year of physics agreed to participate in the study. Five of the seven participants (71.4%) identified as female and two (28.6%) male. Two of the participants identified as Asian, four as white, and one as two or more races. The participants ranged from 9^{th} to 12^{th} grades, with a mode of 11^{th} grade, and had a mean age of 16.71, *SD* = 0.95. For their first year of physics, four participants were enrolled in a regular physics class, two took honors physics, and one took AP Physics 1. While enrolled in physics, the participants were co-enrolled in different mathematics classes including Algebra 3, Geometry, Pre-Calculus/Trig, AP Calculus AB, and AP Statistics.

The seven participants attended five different schools in the eastern United States. The profiles of individual participants are shown in Table 4.

Table 4

Demographic Profiles of the Seven Participants

Name*	Gender	Race/Ethnicity	Age	Grade	Physics Class	Math Class
Lana	female	Two or more	18	12	Physics	Pre-Calculus/Trig
Judy	female	Asian	16	11	Physics	AP Calculus AB
Samir	male	Asian	17	11	Honors Physics	Pre-Calculus/Trig
Catherine	female	White	15	9	Physics	Geometry
Aaron	male	White	17	11	Physics	Algebra 3
Jessica	female	White	17	11	Honors Physics	Pre-Calculus/Trig
Ellie	female	White	17	11	AP Physics 1	AP Calculus AB & AP Statistics

*Pseudonym

Measures

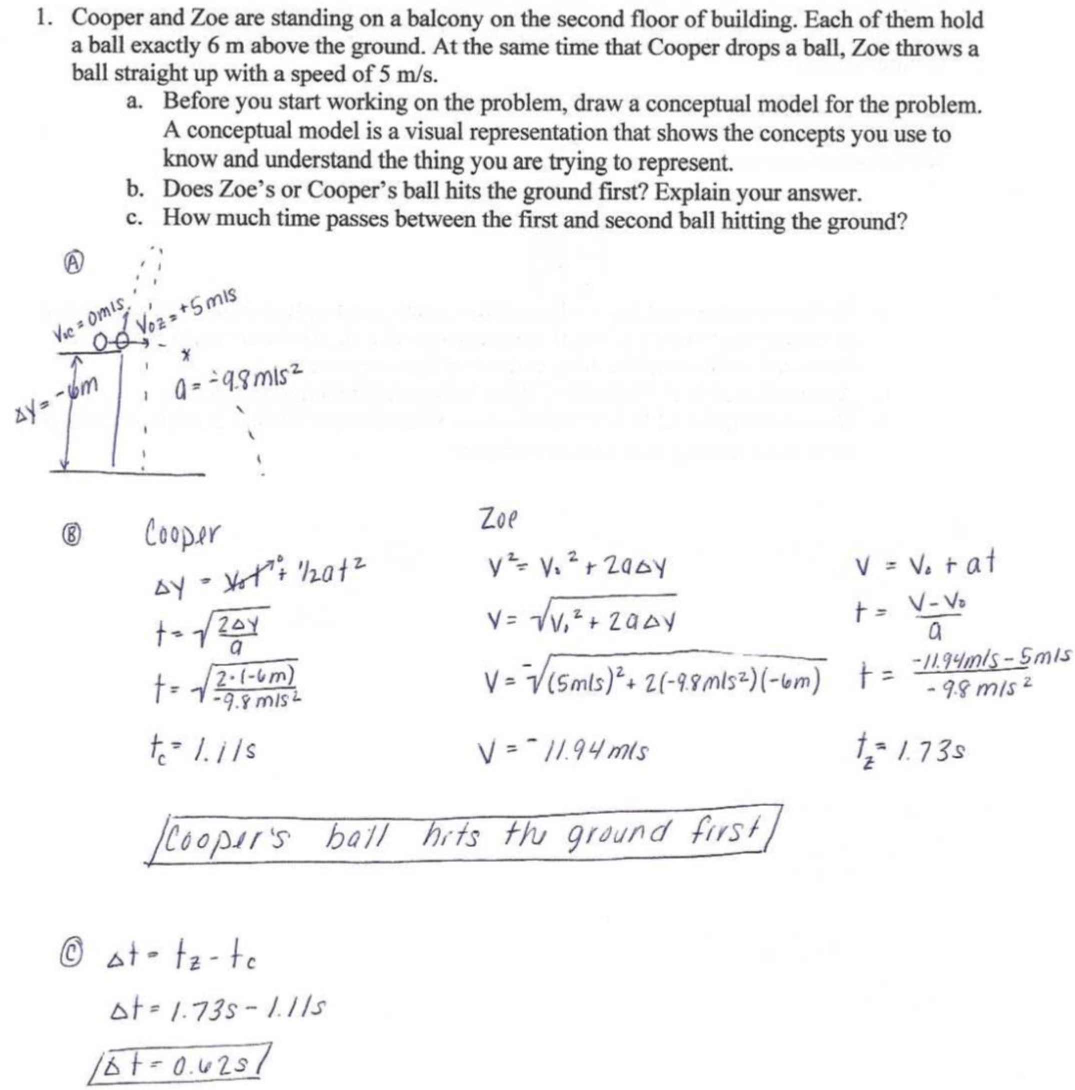
The parental consent form (Appendix A), student assent form (Appendix B), demographic information (Appendix C) and PMI (Appendix D) were administered to all participants at the beginning of the virtual interview using a Qualtrics questionnaire, prior to the think aloud. In the think aloud, participants were asked to solve three physics problems (Appendix E). The physics problems asked questions that covered the physics concepts of projectile motion, Newton's 2nd Law, and uniform circular motion. These are concepts commonly taught early in the physics curriculum, increasing the likelihood those physics topics were studied by the participants prior to the shift to virtual schooling.

Student Demographic Information. Student demographic information included participant (a) name, (b) age, (c) gender, (d) race/ethnicity, (e) grade level (9-12) during the 2019-2020 school year, (f) physics course, (g) high school, and (h) mathematics class during the 2019-2020 school year. Participant names were needed to match participant's data to consent forms. To ensure that study identities were kept anonymous, each participant was assigned a pseudonym, a key linking participant names and pseudonym was created in a separate document, and then participant data was deidentified.

Physics Metacognitive Inventory. The Physics Metacognitive Inventory (PMI, Appendix D) was used to measure the participant's use of metacognitive strategies that are typically used while solving physics problems. The PMI is a 26-item self-report survey that uses a five-point Likert-type scale. The scale ranged from (1) never true of myself to (5) always true of myself. The 26 items measured six factors of metacognition: (a) knowledge of cognition: declarative, procedural, and conditional, (b) regulation of cognition: information management, (c) regulation of cognition: monitoring, (d) evaluating, (e) regulation of cognition: debugging, and (f) regulation of cognition: planning (Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013). The PMI item reliability was 0.97 (excellent) and the person reliability was 0.86 (good) for the 285 introductory college level physics students who participated in the study (Taasoobshirazi et al., 2015). Although the study was initially validated with introductory college level physics students, the PMI is appropriate for both high school and college physics students because the questions do not include any physics content and were confirmed to be at a 6th grade reading level (Taasoobshirazi et al., 2015). Participant use of metacognitive strategies was recorded as the mean overall PMI score where one is low use of physics metacognitive strategies and five is high use. Qualtrics was used to collect participant demographic information and responses to the PMI.

Physics Problems. The participants were asked to solve three physics problems during the think aloud (Appendix E). Two of the problems were developed by the researcher and the third problem was a ranking task from the nTIPERS book (Hieggelke et al., 2012). These three problems were chosen because they align with the concepts tested in the Force Concept Inventory, which was part of the original study plan: problem number one was projectile motion problem, problem number two covered Newton's second law, and problem number three asked about uniform circular motion. Although the Force Concept Inventory was no longer being used, these concepts were ideal to cover since they are topics that are usually covered in the early part of the school year. This ensures that participants would have learned these topics in an in-person classroom, with typical resources and teaching strategies, prior to schools going virtual due to COVID-19 in the Spring of 2020. When developing or choosing the problems, I wanted to ensure that the physics problems were hard enough that students would be encouraged to engage in metacognition while solving the problems, but not so hard that students would not be able to answer them and therefore be discouraged. The problems were validated by three researchers who have past experience teaching high school physics to confirm the problems (a) covered appropriate content, (b) were at an appropriate level of difficulty for the participants, and (c) should take less than a total of 30 minutes to complete. While working through the problems, the participants were allowed to use a calculator and had a list of physics equations for reference. These physics equations are the same kinematics and force equations that are provided on the AP Physics I exam (College Board, 2020).

Explanation of Conceptual and Computational Demands of Problems. Problem one was a one-dimensional kinematics free fall problem with three parts. Figure 9 shows one example of how problem one could be solved. Part A asked for a conceptual model for the problem. Part B asked which ball would hit the ground first and could be answered computationally or conceptually. And part C was a computational question asking for the amount of time that passed between the two balls hitting the ground. Within the wording of problem one, there were two covert given quantities, information given as words and concepts instead of directly listing the quantity: (a) if an object is dropped, its initial velocity is zero, and (b) when objects are in free fall, they fall at the acceleration due to gravity.



1. Cooper and Zoe are standing on a balcony on the second floor of building. Each of them hold a ball exactly 6 m above the ground. At the same time that Cooper drops a ball, Zoe throws a ball straight up with a speed of 5 m/s.
    a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.
    b. Does Zoe's or Cooper's ball hits the ground first? Explain your answer.
    c. How much time passes between the first and second ball hitting the ground?

(B) Cooper

$\Delta y = v_0 t + \frac{1}{2}at^2$

$t = \sqrt{\frac{2\Delta y}{a}}$

$t = \sqrt{\frac{2\cdot(-6m)}{-9.8 m/s^2}}$

$t_c = 1.11s$

Zoe

$v^2 = v_0^2 + 2a\Delta y$

$v = \sqrt{v_0^2 + 2a\Delta y}$

$v = -\sqrt{(5m/s)^2 + 2(-9.8m/s^2)(-6m)}$

$v = -11.94 m/s$

$v = v_0 + at$

$t = \frac{v - v_0}{a}$

$t = \frac{-11.94m/s - 5m/s}{-9.8 m/s^2}$

$t_z = 1.73s$

Cooper's ball hits the ground first

(C) $\Delta t = t_z - t_c$

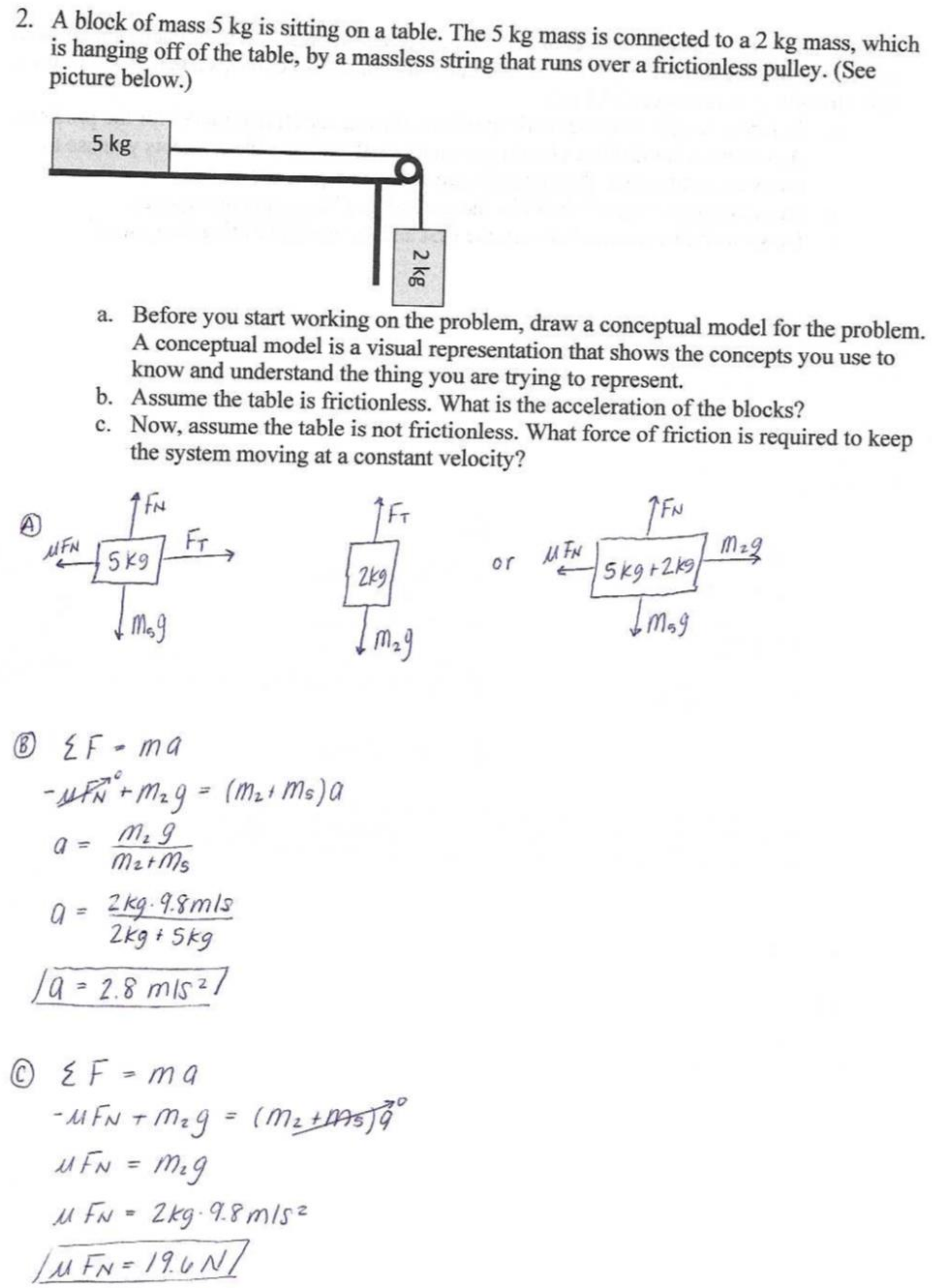
$\Delta t = 1.73s - 1.11s$

$\Delta t = 0.62s$

Figure 9.

Example solution for problem one

Problem two was a two-dimensional Newton's second law problem with three parts. Figure 10 shows one example of how problem two could be solved. Part A asked for a conceptual model for the problem. Part B asked for the acceleration of the blocks, which required a computational solution. Part C asked for the force acting on the blocks given a specific situation. Although part C was a computational question, participants could have used their conceptual understanding of the problem in combination with calculations they already completed in part B without doing additional calculations. Participants engaged with problem two would need to understand three major concepts addressed in the wording of the problem: (a) that a constant velocity signifies an acceleration of zero, (b) that the two objects connected by the string will move at the same acceleration, and (c) how to approach the situation both with and without friction.


2. A block of mass 5 kg is sitting on a table. The 5 kg mass is connected to a 2 kg mass, which is hanging off of the table, by a massless string that runs over a frictionless pulley. (See picture below.)

a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.
b. Assume the table is frictionless. What is the acceleration of the blocks?
c. Now, assume the table is not frictionless. What force of friction is required to keep the system moving at a constant velocity?

Ⓑ $\Sigma F = ma$

$-\mu F_N^{\,0} + m_2 g = (m_2 + m_5)a$

$a = \frac{m_2 g}{m_2 + m_5}$

$a = \frac{2kg \cdot 9.8 m/s}{2kg + 5kg}$

$a = 2.8\ m/s^2$

Ⓒ $\Sigma F = ma$

$-\mu F_N + m_2 g = (m_2 + m_5)a^{0}$

$\mu F_N = m_2 g$

$\mu F_N = 2kg \cdot 9.8 m/s^2$

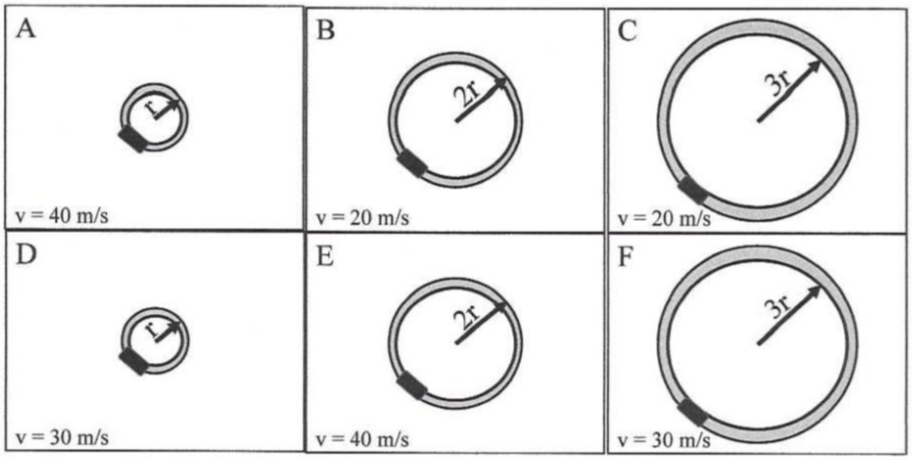
$\mu F_N = 19.6 N$

Figure 10.

Example solution for problem two

Problem three was a uniform circular motion problem with three parts. Figure 11 shows one example of how problem three could be solved. Part A asks for a conceptual model for the problem. Part B asks for the net force acting on the cars to be ranked from greatest to least. In addition to ranking the forces, the participant also had the option to declare that (a) all of the forces were the same, but not zero, (b) all of the forces were zero, or (c) the participant did not have enough information to determine the ranking. The correct answer requires the participant to computationally solve the problem. Part C asks the participant to explain their reasoning. Problem three had two conceptual clues built into the wording of the problem. The problem stated that the cars are driving at a constant speed around a circular track. From this statement, the participant would need to understand that while the speed is not changing, the direction of the car is constantly changing, and thus it is accelerating. Additionally, it was the same car for each situation, so the masses are all the same, therefore it is not necessary to know the of the mass of the cars to rank the forces on the cars.

3. In each case below, a small car is traveling around a circular track at a constant speed. The radii of the tracks and the speeds of the cars are given for each case.



a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.

b. Rank the magnitude of the net force acting on the car on these tracks.
Greatest 1 _A_ 2 _D_ 3 _E_ 4 _F_ 5 _B_ 6 _C_ Least
OR, _____ The magnitude of the net force on the car is the same but not zero for all these tracks.
OR, _____ The magnitude of the net force on the car is zero for all these tracks.
OR, _____ We cannot determine the ranking for the magnitude of the net force on the car.

c. Please explain your reasoning.

(A) $\Sigma F = ma$

$\Sigma F = m\frac{v^2}{r}$

(B) A D E F B C

(C) $m_A = m_B = m_C = m_D = m_E = m_F$

$a_A = \frac{1600\ m^2/s^2}{r}$ $a_D = \frac{900\ m^2/s^2}{r}$

$a_B = \frac{400\ m^2/s^2}{2r} = \frac{200\ m^2/s^2}{r}$ $a_E = \frac{1600\ m^2/s^2}{2r} = \frac{800\ m^2/s^2}{r}$

$a_C = \frac{400\ m^2/s^2}{3r} = \frac{133\ m^2/s^2}{r}$ $a_F = \frac{900\ m^2/s^2}{3r} = \frac{300\ m^2/s^2}{r}$

5

Figure 11.

Example solution for problem three

Think Aloud Protocol. A think aloud protocol was used to capture the participants' though processes while solving the three physics problems (Ericsson & Simon, 1993; van Someren et al., 1994). During the think aloud, participants were asked to verbalize their thought process while solving three physics problems. Following a typical think aloud protocol, I only addressed the participants before the task began in order to give instructions. The only interaction I had with the participants during the task was to encourage the participants to continue to share their thinking if they paused for an extended time (Ericsson & Simon, 1993; van Someren et al., 1994). This protocol allowed me to hear the uninterrupted thought process of the participants. This type of think aloud, where the researcher only asks the participant to verbalize their thoughts, provides a more accurate measure of metacognition because the participant is not asked for additional information or explanations beyond the participants normal thought process (Double & Birney, 2019).

Follow-up Question. After the participants finished working on the three physics problems, they were asked one open-ended interview question, "Thinking across all of the problems, is there anything in particular that you noticed about how you solve problems?" This reflective question allowed participants to share additional information they may have not shared during the think aloud.

Procedure

The following procedure was repeated for each of the seven participants in an attempt to be as consistent as possible. Shortly before the individually scheduled interviews, a secure link to my personal Webex meeting room was sent to the participant.

Additionally, the participant was emailed a pdf that included the example think aloud questions, physics equation sheet, and three physics problems for the think aloud interview. The participant was asked to print, but not review, the questions prior to the think aloud interview.

The virtual interview was conducted in a private, quiet room in my and the participant's homes. Once the participant was signed on to the Webex meeting, a link was sent to them using the chat feature of Webex. The link led the participant to the Qualtrics survey that contained the parental consent form, student assent form, demographic information, and PMI. The Qualtrics survey was designed so that no participant information was collected until the parental consent and student assent forms were completed.

Once the participant finished filling out the entire survey, I began the think aloud interview. During the interview, the participant was asked to solve three physics problems while sharing their cognition and metacognition out loud. The participant was encouraged to have a calculator available to use while working on the physics problems. The entire think aloud protocol was recorded using the Webex recording feature. The recording was not started until after the participant completed the survey to ensure consent and assent forms were signed.

Once the participant was settled with their copies of the problems and the recoding was started, I began the think aloud interview by reading the script (Appendix F):

> I am going to ask you to work on three physics problems. While you are working on the three problems, I want you to think aloud. This means that any thought you have while working on the problem, no matter how unimportant you may think the thought is, you are to say it out loud. I want to understand your thought process while working on physics problems. Before I have you work on the physics problems, I am going to demonstrate a think aloud for you and have you practice thinking aloud while completing a puzzle. If at any time you want to stop participating in the study, you are welcome to do so. Do you have any questions for me before we begin?

After I read the script, I demonstrated a think aloud protocol using the first of two non-physics-based logic puzzles (Ericsson & Simon, 1993). When I finished the first example and confirmed that the participant did not have any questions, I had them practice a thinking aloud while working on the second non-physics-based logic puzzle (Ericsson & Simon, 1993; van Someren et al., 1994). Once the participant completed their practice think aloud, I again checked if they had any questions before proceeding to the physics problems.

During the physics portion of the think aloud, the participant was asked to work through three physics problems (Appendix E). I started the physics portion of the physics problem think aloud by reading the following statement:

> In your packet are three physics problems. Please work through them one at a time. While you are working, please say every thought that goes through your mind. You may use a calculator and the given equations if needed.

During the think aloud protocol, I only interrupted the participant if they stopped talking and probed them with a phrase such as “please say everything that goes through your mind” or “keep talking” (Ericsson & Simon, 1993; van Someren et al., 1994).

When the participant had finished all three problems, I asked one follow-up question “Thinking across all of the problems, is there anything in particular that you noticed about how you solve problems?” Once students were done answering the question, I thanked them for their participation and stopped the recording. I also asked participants to email me a picture or scan of their work on the problems.

Analysis

Quantitative Analysis. Excel was used to calculate all descriptive statistics. Descriptive statistics were run for participant demographic information and PMI scores. These statistics included means, modes, medians, standard deviations (SD), and percentages where appropriate. Due to the small sample size, as additional form of central tendency, median, was used in addition to mean and standard deviation. PMI scores were also used to determine each participant’s self-reported, most frequently used metacognitive strategies while solving physics problems.

Qualitative Analysis. Recordings were transcribed verbatim (van Someren et al., 1994). Any field notes originally taken during the think aloud were also incorporated into the transcriptions (Carspecken, 1996). Since video was included in the Webex recordings, participant gestures of importance were included in the notes in the transcription.

The transcriptions were coded in three rounds using Dedoose. A list of a priori codes is shown in Table 5 and the full codebook with examples is in Appendix G. The first round of coding mapped out the participant's problem solving process using the a priori codes shown in Table 5 (Johnson & Christensen, 2014). Because of COVID-19, I was limited in the way that I was able to measure cogntion. I chose to use this problem solving framework to measure cogntion because it was observable. These codes were developed by combining Phang's (2009, 2010) problem solving model with the problem solving process typically described in physics textbooks (Etkina et al., 2014; Knight, 2013). The second round of coding mapped out the participant's metacognitive process using a priori codes for the eight subprocesses of metacognition as shown in Table 5 (Schraw, 1998; Schraw & Dennison, 1994; Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013). These codes align with the constructs measured in the PMI (Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013). The regulation of cognition subprocess of planning was split into three codes (strategy, allocating resources, and goal setting) to better explain the student's metacognition. The final round of coding was open coding for other emergent themes beyond problem solving and metacognition (Carspecken, 1996). Three emergent codes transpired from the think aloud data.

Table 5

List of A Priori Codes for Student Physics Problem Solving and Metacognitive Processes

Problem Solving	Metacognitive Process
Reading	**Knowledge of Cognition**
Rereading	Declarative
Planning	Procedural
Draw a picture or diagram	Conditional
Arrange Information	**Regulation of Cognition**
List knowns and unknowns	Planning
Choose a concept or equation	Strategy
Calculating	Allocating Resources
Answering	Goal Setting
Checking	Information Management
	Comprehension Monitoring
	Debugging
	Evaluation

During the think aloud interviews and transcription process, I noticed that when the participants were explaining their reasoning for doing a problem, three additional themes emerged (a) teacher influence or expectations, (b) problems as assessments, and (c) common sense or logic. Excerpts related to these themes were noted in the coding process. These excerpts were organized in a matrix and then a name for the code was assigned based on the interpretation of the excerpt. Of the total 531 excerpts coded, the emergent codes were applied to 33 of the excerpts (6.2%). After the coding was completed, it was confirmed that those three themes were each addressed by multiple participants at different parts of the think aloud, verifying their emergence. Table 6 has four examples of excerpts for each of the three emergent codes. A full list of excerpts coded with the three emergent codes is in Appendix H.

Table 6

Four Example Excerpts from Think Aloud Interviews Coded with the Three Emergent Codes

Teacher Influence or Expectations	Problems as Assessments	Common Sense or Logic
"Also like what information do I need, um, in the problem that could make me answer the problem quicker. Cause like, sometimes if it was like, a trick question, um I know my teacher did that a lot this year, um, to make sure we were really reading it. So, I have learned to like make sure I read each problem carefully and then, like, double checking my work, I guess." (Catherine) "Wait, (pause) ah, no no no. What I've been taught because I'm also thinking I know I've been taught to, ah, isolate, you know, the variable first before plugging in numbers. Um, I personally don't see the, I personally prefer just plugging the numbers in and isolating from there. So, I'm just do what I would normally do, and just plug in the numbers" (Samir) "Yeah, my, my teacher had us do this all the time. Like, whenever we did problems, she would have	"I don't know, I think that's all. I, I know I don't really check my work. Like, if it was a test, I would, um (pause) I don't know, I never really run the numbers again, but I would just look over it and make sure it makes sense again before I moved on to the next problem. But otherwise if it's not like an exam, I'm not really a work checker." (Ellie) "Usually, if I were doing a problem like this, like, if I had this on the test, I'm skipping this problem. I'm going right to the next one, um, because this is like, me, not studying for like a week. And this is a really big test." (Aaron) "So we'll just say, for the sake of just getting an answer, which is what I would do on tests, all the time. And sometimes it would be right. And I would just be very happy." (Aaron) "So, I think I would probably leave this if I	"I tried to apply logic to all of them. Like, what like, my own knowledge on, like, how objects interact with each other and gravity around them in the forces that I know exist." (Lana) "So initially, just common sense wise, I'm thinking that Cooper's ball is gonna hit the ground first, because they're both standing in the same location but Cooper's just dropping it straight down whereas Zoe is throwing it up initially. So common sense wise I know that my answer should be Cooper. Um, it says to explain my answer." (Ellie) "I don't know, I think that's all. I, I know I don't really check my work. Like, if it was a test, I would, um (pause) I don't know, I never really run the numbers again, but I would just look over it and make sure it makes sense again before I moved on to the next problem. But otherwise if it's not like an

us go up on the board, write them down, and explain to the class how we did it. So, this is like, second nature for me now." (Aaron) "I wouldn't think it would be zero, because that's just kinda seems pointless as a question in general. Like, I wouldn't expect them to give me such an easy answer. So, I'm going to cross that one out." (Judy)	was, if I were doing a test, because at least I showed some effort. So here's my attempt at consoling myself and I would submit this, as it is right now." (Judy)	exam, I'm not really a work checker." (Ellie) "My reasoning is that, okay, (writes while explaining reasoning) my reasoning is based off of process of elimination as well as logical reasoning, um, concerning, um, extreme values within a set. I determined the value places based, or wait no. I determined the value places." (Jessica)

Many participants, six out of seven, referenced their teacher during the think aloud interviews. Some of these excerpts were in reference to how their teacher taught them to solve problems such as "Wait, (pause) ah, no no no. What I've been taught because I'm also thinking I know I've been taught to, ah, isolate, you know, the variable first before plugging in numbers." Other excerpts mentioned how a part of the problem was similar or not similar to something their teacher would do, such as "Like, I wouldn't expect them to give me such an easy answer. So, I'm going to cross that one out." In total, 12 excerpts fit this pattern and were coded as teacher influence or expectations.

In eight instances during the think aloud interviews, participants mentioned how they would approach the problem if it were on an assessment. Most of these excerpts (six of eight) were participants explaining how they would address being stuck on a problem during an assessment "So, I think I would probably leave this if I was, if I were doing a test, because at least I showed some effort." A few excerpts noted how participants use different strategies on an assessment as compared to regular problem solving, for instance the statement “But otherwise if it's not like an exam, I’m not really a work checker.” In all, four of the seven participants made statements that were coded as problems as assessments.

The common sense or logic code was used for excerpts where the participant overtly made reference to using common sense or logic to solve the problems. Many participants used common sense or a logic based explanation when working on the problems, but this code was only applied when the participant specifically used phrases like “I tried to apply logic” or “just common sense wise.” The common sense or logic code was applied to excerpts from four of the seven participants for a total of 13 excerpts.

A fourth round of coding was done using hard copies of the transcriptions and highlighters rather than Dedoose. This approach made it easier for me to take a clean look at the transcripts, without the other codes visible, while listening to the think aloud interviews. Each interview was reviewed looking for statements where the participant indicated dissatisfaction with their understanding. Dissatisfaction was identified as a comment where the participant indicated that they were confused by or did not understand something about the problem. This could mean they were dissatisfied with their understanding of the physics concepts needed to solve the problem or they were dissatisfied with their understanding of the information given in the problem. In doing so, the participant interrupted their thought process to make the statement. In addition to the words stated, I listened for the tone of voice, a change in pace, and other auditory clues that the participant was not satisfied with their understanding. Once each instance of dissatisfaction was located, behaviors were recorded before and after the dissatisfaction in order to understand what the participant was doing to prompt the dissatisfactions as well as what the participant did next as a result of the dissatisfaction. Appendix I contains the full list of statements marked as noting dissatisfaction.

The dissatisfaction statements came in a variety of levels of clarity and length. Some statements, such as "which is very conceptual and I'm confused by it already," demonstrate the participant's dissatisfaction with their understanding. Other statements, such as "I see what I did here," may not as clearly indicate dissatisfaction taken out of the context of the interview. Some of the statements of dissatisfaction of their own learning were very short and explicit, "Yeah, I don't understand this one, so" (Judy), while other statements were longer and gave more insight into how the dissatisfaction made the participant's feel:

> We're, we're just gonna move on from question A question B right now. Because I can't remember why I did that, and maybe whenever I go through the second question, it'll help me like just regroup. And I feel very chaotic right now (Aaron).

In total, 51 statements where coded as instances where a participant expressed dissatisfaction.

A second coder independently coded two (29.6%) think aloud transcriptions to ensure intercoder reliability. The second coder was a former physics teacher working on their PhD in science education research. I met with the second coder prior to coding to review the codes and provided references for clarification. After the second coder and I completed our initial coding of the two interviews, codes were compared and checked for coder agreement. Table 7 shows the coder agreement totals after the first round of coding. As suggested by McAlister et al. (2017), Miles and Huberman's (1994) calculation for inner-coder reliability was used to calculate the consistency between coders. Codes where the researcher and second coder coded with full agreement as well as codes with a slight difference were both counted as number of agreements. Inner coder reliability was calculated to be 77.4%. I met with the second coder and discussed each code until 100% consensus was met.

Table 7

Coder Agreement Totals for Comparison of the Researcher and Second Coder for Initial Coding

Codes where:	**Interview 1**	**Interview 2**	**Total**
Only researcher coded	17	7	24
Only second coder coded	29	19	48
Both researcher and second coder coded with slight difference	32	30	62
Both research and second coder coded with full agreement	112	72	184
Total	190	128	318

Integrated Analysis. In the integration phase, participant PMI responses were combined with the coding analysis from their think aloud transcriptions. Quantitative data was qualified, and qualitative data was quantified. In doing so, quantitative data was supported by qualitative data and vice versa. A joint display was used to aid in the analysis (Guetterman et al., 2015). The joint display presented the participants' (a) PMI descriptive statistics, (b) most frequently used metacognitive strategies as self-reported in the PMI, (c) quantity of metacognitive statements from the think aloud, and (d) most frequently used metacognitive strategies from the think aloud (Guetterman et al., 2015).

Eight similarity matrix heatmaps were created to demonstrate the code co-occurrence of statements from the think aloud that were coded for both physics problem solving and metacognitive processes: one heatmap for the overall totals and one for each participant. The heatmaps were created using the code co-occurrence analysis tool in Dedoose by including statements that were double coded for a physics problem solving strategy and a metacognitive strategy, as well as statements coded with one type of strategy that overlapped with a statement coded for the other. The heatmaps were color coded so the red squares indicate the ten most frequently observed code co-occurrences, followed by orange, yellow, and then white with the ten least frequently observed code co-occurrences.

For each participant, a case was written to describe how they used cognition and metacognition while solving physics problems. The cases integrated qualitative descriptions of the participant's interview, participant work samples, quantitative analysis of qualitative data, and participant responses to the PMI. Each case started with a summary of the participant's problem solving think aloud and their individual heatmap. This was followed by a description of how the participant approached the three physics problems. This description included how they used cognition and metacognition while solving the physics problems, as well as if they shared dissatisfaction with their knowledge during the think aloud.

Validity

Maxwell (2013) defined validity as “the correctness or credibility of a description, conclusions, explanation, interpretation, or other sort of account” (p. 122). This definition puts the focus of validity on the relationship between reality and inferences rather than just the methods used in the study. In an attempt to increase validity, a researcher must actively employ strategies to limit the impact of threats to validity. The two main threats to validity are researcher bias and reactivity (Maxwell, 2013). Research bias refers to the theories, beliefs, and lenses that influence the researcher’s interpretation of the data. While it is not possible to eliminate researcher bias, it is important for the researcher to recognize these potential biases and work to use strategies to lessen their impact. Reactivity is the influence of the researcher on the participants or the setting of the study (Maxwell, 2013). In the following sections, I will address possible issues of research bias and reactivity as well as strategies used to limit the impact of validity threats to this study.

Research Bias. I am a former physics teacher with an undergraduate degree in physics. I taught physics for 12 years at varying levels of physics including Conceptual Physics, Regular Physics and AP Physics 1 at three different high schools. While my expertise helps increase the validity of the claims I made, it could also provide bias in my coding. With my experience of working with physics students while solving physics problems, it is possible that I may have read into the participants’ statements and inferred beyond their statement. To help mitigate this possible bias, I worked to limit the inferences made while coding and had a second coder independently code the think aloud transcripts. Additionally, I had three researchers who were former physics teachers assess the three physics problems used in the study to ensure the problems covered appropriate concepts at an appropriate level of difficulty. This helped to decrease researcher bias.

Reactivity. For certain methods of measuring metacognition, reactivity, or a participant changing their behavior in response to the measure or researcher, can be problematic (Double & Birney, 2019). Think aloud protocols that only ask a participant to verbalize their thoughts, as used in this study, were found not to be reactive, providing a more accurate measure of metacognition (Double & Birney, 2019). The choice of think aloud protocol to measure metacognition in addition to the PMI limits the potential reactivity. To further limit the researcher's influence on the participant, I read from a script for all parts of the study to ensure that all participants heard the same instructions and received the same prompts as they worked through both the quantitative and qualitative portions of the study.

Strategies to Limit Validity Threats. Maxwell (2103) provides a list of potential strategies for researchers to engage with in order to limit possible validity threats. For this study, those strategies included the use of: (a) rich data, (b) triangulation, (c) numbers, and (d) discrepant evidence.

Rich Data. Rich data are detailed and varied to provide a full picture of the phenomena at hand (Maxwell, 2013). For this study, video recordings were transcribed verbatim with researcher notes and descriptions of actions added when appropriate. In addition to transcripts of the think aloud interview, student work for the physics problems completed during the think aloud were collected.

Triangulation. Triangulation refers to collecting data from a variety of individuals, settings, or methods (Maxwell, 2013; Shenton, 2004). In this study, triangulation refers to the use of both quantitative and qualitative measures of student use of metacognition while solving physics problems. The quantitative measure, the PMI, is specifically designed to assess specific metacognitive uses for solving physics problems rather than general metacognitive processes and has been validated for participants similar to those in the study (Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013). The qualitative measure, the think aloud analysis, used codes developed from the same definitions of metacognitive processes as those used in the PMI. The triangulation of PMI scores and think aloud coding results will help to increase the validity of conclusions drawn from the evidence (Maxwell, 2013; Shenton, 2004).

Numbers. The use of numbers in a qualitative study, or quasi-statistics, helps to support claims by making them more explicit or precise (Maxwell, 2013). When possible, specific number of participants, coded statements, or examples of student work were used in the justification of claims.

Discrepant Evidence. It is just as important to identify evidence that goes against the stated claim as it is to find evidence that supports it. By analyzing discrepant evidence and taking it into account when making conclusions, the validity of conclusions increases (Maxwell, 2013). The research questions for this study asked how students use metacognition and in what ways do students voice dissatisfaction. To answer these questions fully, it is just as important to note how students do use metacognition or voice dissatisfaction as it was to note how they do not use metacognition or voice dissatisfaction. Discrepant evidence was used to compare the different experiences of participants.

Ethical Considerations

IRB approval was received from George Mason University's Office of Research Integrity and Assurance prior to working with participants (Appendix I). I explained the purpose and procedures of the study to the participants in the recruitment email as well as during the study itself. Consent forms (Appendix A) were filled out by the participant's parent or guardian and assent forms (Appendix B) were filled out by the participant at the time of the virtual interview. No participant was allowed to participate in the study unless both the consent and assent forms were signed. Additionally, pseudonyms were used to assure participant anonymity.

Chapter Four

High school physics students enter the classroom with a wealth of beliefs, knowledge, and experiences that help them understand and explain physics concepts; however, these may not fully align with the scientifically accepted concepts (Disessa, 1996; Gunstone et al., 1992; von Aufschnaiter & Rogge, 2010; Vosniadou, 1994). According to conceptual change theory, for a student to start the process to change their conception, they need to first be dissatisfied with their current conception (Dole & Sinatra, 1998; Posner et al., 1982). To engage with their conception in such a way that they would possibly be dissatisfied with it, the student must be metacognitive (Flavell, 1979). This mixed methods study used the Physics Metacognitive Inventory (Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013) and a think aloud interview protocol (Ericsson & Simon, 1993; van Someren et al., 1994) while participants solved physics problems to investigate how current physics students use cognition, metacognition, and dissatisfaction while solving physics problems. The following research questions were addressed:

1. How do current high school physics students use cognition and metacognition to solve physics problems?
2. In what ways do current high school physics students voice dissatisfaction with their content knowledge while solving a physics problem, and does that dissatisfaction lead to conceptual change?

In this chapter, I will first explain the data sources used to answer the two research questions. These data sources include participants' responses to the Physics Metacognitive Inventory, think aloud interview transcriptions, and student work from three physics problems. Because of overlap in the data sources used to answer the research questions, I will next elaborate on the overall data analysis before I address the research questions. This will include discussing the individual cases of each of the seven participants. I used individual cases for the participants because it is important to hear how each participant approached the three problems. Finally, I will return to the two research questions stated above and review overall themes to answer each question.

Participants

A snowball approach was used to recruit seven participants for this study. Each participant was a high school physics student who had just completed their first year of an Algebra I based physics class (see Table 4). Of the seven participants, five identified as female and two as male. Two of the participants identified as Asian, four as white, and one as two or more races. They ranged in age from 15 to 18 with an average age of 16.71, *SD* = 0.95. The participants took different levels of physics (Physics, Honors Physics, and AP Physics 1) as their first-year physics course. One participant took their physics course during their freshman year of high school, one during their senior year, and the rest during their junior year. The seven participants attended one of five different schools in the eastern United States.

Procedures

Each participant was asked to complete the PMI (Appendix D) and solve three physics problems while participating in a think aloud interview (Appendix E). The PMI recorded participant responses indicating how often they typically used one of 26 different metacognitive strategies for solving physics problems. Within the 26 items on the PMI, there were two statements for each of the three knowledge of cognition statements: (a) declarative, (b) procedural, and (c) conditional, and three to five statements for each regulation of cognition process: (a) planning, (b) information management, (c) comprehension management, (d) debugging, and (e) evaluation.

After completing the PMI, each participant was asked to solve three physics problems. While the participants completed the problems, they were asked to share all of their thoughts out loud throughout the entire problem while the researcher recorded the conversation. When the participants were finished solving the three problems, they were asked one follow up question, “Thinking across all of the problems, is there anything in particular that you noticed about how you solve problems?”

The problems the participants were asked to solve, while sharing their thought processes, covered kinematics, Newton’s 2^{nd} Law, and uniform circular motion. As explained in Chapter 3, in Table 8, each of the three problems had three parts which were chosen to demonstrate different problem solving approaches. Table 8 shows by problem: (a) number of parts, (b) the physics concept addressed, (c) the type of solution needed, and (d) the covert conceptual clues in each problem. A conceptual solution means that the problem can be solved using only conceptual understanding and does not require the use of numbers or equations. A computational solution means that the problem asks for a numeric answer that requires the use of numbers and equations. Covert conceptual clues are the numerical quantities or understandings given in the wording of each problem rather than overtly given as numeric quantities that were critical to solve the problem. Part A for each problem asked the participant to draw a conceptual model for the problem. Parts B and C for the three problems posed questions to students that could be answered in either a conceptual or computational manner.

Table 8

Summary of The Physics Problems Used in the Think Aloud Interview

Problem		Physics Concept	Solution Type	Covert Conceptual Clues
1	A	1-D Kinematic Freefall	Conceptual	Dropped → $v_o = 0$ m/s Freefall → $a = g = 9.8$ m/s^2
	B		Conceptual or Computational	
	C		Computational	
2	A	2-D Newton's Second Law	Conceptual	Constant velocity → $a = 0$ m/s^2 Connected by string → same a Friction vs frictionless
	B		Computational	
	C		Computational	
3	A	Uniform Circular Motion	Conceptual	Constant speed in circle → direction is changing → $a \neq 0$ m/s^2 Same mass → can rank F without m
	B		Computational	
	C		Conceptual	

Think aloud interviews were transcribed verbatim and then coded for physics problem solving processes, and metacognitive process (see Table 5 for the a priori codes and Appendix G for the complete codebook including emerging codes). Additionally, think aloud interviews were coded for statements of dissatisfaction, making note of what the participant was doing prior to and immediately following the statement of dissatisfaction (Appendix I).

While conducting, transcribing, and coding the think aloud interviews, I noticed that in addition to sharing their cognition and metacognition, multiple participants mentioned other experiences to help explain how they were thinking about the problems. These statements made by the participants were grouped into three emergent codes: (a) teacher influence or expectations, (b) problems as assessments, and (c) common sense or logic (see Table 6 for examples of each emergent theme or Appendix H for a full list of statements coded for each emergent code). Each of these emergent codes was mentioned by multiple participants and ranged from 8 to 13 statements assigned to each code.

Dedooses' code co-occurrence analysis tool, which displays the frequency at which each code was applied at the same time as other codes, was used to better understand where in the problem solving process participants, both individually and collectively, were engaging in metacognition. A heatmap was created for each participant and for overall totals showing the frequency of events when both metacognition and cognition, problem solving processes, were occurring simultaneously in the think aloud interview.

In order to understand cognition, metacognition, and dissatisfaction of the participant, cases were written for each participant using the quantitative data analysis from the PMI and qualitative data analysis of the think aloud interviews. As shown in Table 9, data from the PMI and the think aloud interview were used to answer research question one, while data from the think aloud interview alone were used to answer research question two. The next section will present overall findings, cases for each participant, and a summary of the results.

Table 9

Data Sources Used to Answer Each Rearch Question

	Research Question	
	RQ1: How do current high school physics students use cognition and metacognition to solve physics problems?	RQ2: In what ways do current high school physics students voice dissatisfaction with their content knowledge while solving a physics problem, and does that dissatisfaction lead to conceptual change?
Data	• Physics Metacognitive Inventory • think aloud interview transcripts • think aloud interview codes • participant work • follow up interview question	• think aloud interview transcripts • think aloud interview coding

Data Analysis

Overall Physics Metacognitive Inventory Results

Prior to engaging in the think aloud interview physics problems, participants took the Physics Metacognitive Inventory (PMI) which has 26 items: six knowledge of cognition items and 20 regulation of cognition items, about an individual's use of metacognitive strategies while solving physics problems. A five-point Likert-type scale was used for the PMI. The scale used was (1) never true of myself, (2) rarely true of myself, (3) sometimes true of myself, (4) usually true of myself, and (5) always true of myself. Descriptive statistics were calculated using the PMI data for overall and individual participant results.

The overall mean for the inventory was 3.59, *SD* = 1.02, with a mode of 4. This means that participants were most likely to respond "usually true of myself" to the statements about metacognitive processes specific to physics problem solving. Tables 10 and 11 display the mean, standard deviation (*SD*), and mode for each of the knowledge of cognition items and the regulation of cognition items respectively. Due to the small sample size, the mode was included as an additional representation of central tendency. Table 10 displays the scores of the knowledge of cognition items by process and Table 11 displays the regulation of cognition items grouped by process. Items with the overall five highest and five lowest means are noted in the table.

Table 10

Descriptive Statistics of Participant Responses to Knowledge of Cognition Items on the PMI (Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013)

	Knowledge of Cognition			
Process	**Item**	**Mean**	***SD***	**Mode**
Declarative	I am a good judge of how well I solve physics problems.	3.29	0.95	4
	When solving physics problems, I know how I work best.	4.14*	0.69	4
Procedural	When solving physics problems, I have a specific purpose for each strategy I use.	3.71	0.95	4
	When solving a physics problem, I know how to apply a strategy to successfully solve the problem.	3.43	0.53	3
Conditional	When solving a physics problem, I know why I'm using a particular strategy.	4.00	0.58	4
	When solving a physics problem, I know when to use a particular strategy.	3.86	0.38	4

Note: Range for all items is from 1-5.
* Item with one of five highest means on overall PMI.

Table 11

Descriptive Statistics of Participant Responses to Regulation of Cognition Items on the PMI (Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013)

	Regulation of Cognition			
Process	**Item**	**Mean**	***SD***	**Mode**
Planning	I think about what a physics problem is asking before I begin to solve it.	4.43*	0.79	5
	Before solving a physics problem, I think about what a reasonable value for the answer would be.	3.29	1.25	2
	Before I start solving a physics problem, I plan out how I'm going to solve it.	3.29	1.38	2
	Before solving a physics problem, I identify all the important parts of the problem.	4.29*	0.76	4
	Before solving a physics problem, I eliminate information in the problem that I don't need.	3.57	1.27	4
Information Management	I draw free-body diagrams to help me solve physics problems.	4.14*	0.69	4
	I use free-body diagrams to help me solve physics problems.	3.86	0.69	4
	I know why free-body diagrams are important for physics problem solving.	3.71	0.95	4
	I draw free-body diagrams for the physics problems I am solving.	4.00	0.58	4
Comprehension Monitoring	While solving a physics problem, I ask myself periodically if I am meeting my goals.	2.71**	0.76	3
	While solving a physics problem, I ask myself questions about how well I am doing.	2.14**	0.90	3
	While solving a physics problem, I periodically evaluate how well I am doing.	2.57**	0.98	3
	While solving a physics problem, I ask myself if I am meeting my goals.	2.71**	0.49	3
Debugging	I ask for help when I don't understand a physics problem.	4.29*	0.76	4
	I seek help when I don't understand the physics problems that I am solving.	4.57*	0.79	5
	I change strategies when I fail to solve a physics problem.	3.57	1.13	4

Evaluation	I go back and check my work after solving a physics problem.	3.14	0.90	3
	After solving a physics problem, I double check my answer.	3.00**	1.15	2
	After solving a physics problem, I look back to see if I did the correct procedures.	3.57	0.98	4
	After solving a physics problem, I look back at the problem to see if my answer makes sense.	4.00	1.00	3

Note: Range for all items is from 1-5.
* Item with one of five highest means on overall PMI.
**Item with one of five lowest means on overall PMI.

The item with the lowest mean (*M* = 2.14, *SD* = 0.90, mode = 3) was the comprehension monitoring item "While solving a physics problem, I ask myself questions about how well I am doing." This indicates that the participants rarely asked themselves how they were doing while they worked on physics problems. The item with the highest mean (*M* = 4.57, *SD* = 0.79, mode = 5) was the debugging item "I seek help when I don't understand the physics problems that I am solving." This indicated that participants almost always sought help with they did not understand.

The items with the five highest mean responses aligned with four metacognitive processes of declarative, planning, information management, and debugging. From the participants' responses, there was no clear metacognitive process that they reported using the most, indicating a possible balanced metacognitive approach to problem solving or lack of awareness of their metacognitive processes. On the other hand, the items with the five lowest mean responses aligned with two metacognitive processes: comprehension monitoring and evaluation. Participants reported rarely or sometimes using metacognitive strategies that helped them to monitor their understanding during and at the end of the problem, an action key to start the process of conceptual change.

Overall Think Aloud Interview Results

Cognition and Metacognition. Each think aloud interview was coded for the participants' use of physics problem solving, the measure of cognition, and metacognitive processes as explained in Chapter 3 (Table 5). The problem solving framework was used as an observable measure of cognition. Table 12 shows the total number of each participant's statements that were coded for each problem solving process. The total number of statements coded for demonstrating the use of a problem solving process per participant ranges from 25 to 85, with an average of 48.29 (*SD* = 23.23). Even though each participant had a unique way of engaging in the problem solving process, for all participants the top two most frequently used problem solving processes were reading and planning. Calculating and checking were the processes with the lowest frequencies of use. Aaron had much higher counts of problem solving processes than the rest of the participants. This is also true of metacognitive processes (Table 13) and dissatisfaction (Table 15). This will be discussed further in his case.

Table 12

Individual Participant's Observed Use of Problem Solving Processes While Solving Physics Problems

	Lana	Judy	Samir	Catherine	Aaron	Jessica	Ellie	Total
Reading	11	16	10	8	20	10	18	93
Planning	9	15	21	13	30	13	35	136
Calculating	0	0	6	7	16	4	6	39
Answering	4	2	10	7	13	4	10	50
Checking	1	0	4	2	6	1	6	20
Total Observation	25	33	51	37	85	32	75	

Table 13 shows the total number of statements by each participant that represented the use of the different metacognitive strategies from the conceptual framework for this study. The total number of statements coded as a metacognitive process per participant ranges from 19 to 84, with an average of 38.14 (*SD* = 21.87). Unlike problem solving statements, the most frequently used metacognitive process is different for each participant. Even when separating out the different types of metacognition, knowledge of cognition and regulation of cognition strategies, the frequency of use of metacognitive strategies was unique for each participant.

Table 13

Individual Participant's Observed Use of Metacognition While Solving Physics Problems

	Lana	Judy	Samir	Catherine	Aaron	Jessica	Ellie	Total
Knowledge of Cognition	12	12	8	4	25	7	12	80
Declarative Knowledge	9	8	2	1	19	2	4	45
Procedural Knowledge	1	2	4	0	2	0	1	10
Conditional Knowledge	2	2	2	3	4	5	7	25
Regulation of Cognition	13	29	26	15	59	17	28	187
Planning	3	6	4	5	11	6	5	40
Information Management	5	7	9	4	7	7	11	50
Comprehension Monitoring	2	12	5	4	23	1	6	53
Debugging	2	4	7	0	10	2	3	28
Evaluation	1	0	1	2	8	1	3	16
Total Observation	25	41	34	19	84	24	40	

Overall, the participants used comprehension monitoring, information management, and declarative knowledge the most in the think aloud interview. These metacognitive processes seemed to work together as the participants tried to figure out what they understood and what information they had in order to solve the problems at the beginning of the problem solving process. The least frequently used metacognitive processes were procedural knowledge, evaluation, and conditional knowledge. Participants were more likely to use and regulate their cognition than they were to explain how or why they were using it. This mostly aligned with the PMI results. Information management and declarative knowledge both had one statement that was one of the top five highest average scores on the PMI and evaluation had one statement as one of the five lowest average scores. Both procedural knowledge and conditional knowledge had average PMI scores that were neither in the groupings of highest or lowest scores. The alignment of PMI scores and think aloud interview frequencies shows that participants had a good understanding of the frequency they used those metacognitive processes. Comprehension monitoring was an interesting case in that it was one of the lowest scoring processes on the PMI, but the process with the largest number of observations in the think aloud interview. It is possible that the participants did not recognize how often they checked their comprehension while working on the problems since it happened during the problem solving process and is not viewed as a separate step in the problem solving process like checking/evaluation was.

Table 14 is a display that exhibits the participants' (a) PMI descriptive statistics, (b) most frequently used metacognitive strategies as self-reported in the PMI, (c) quantity of metacognitive statements from the think aloud interview (from Table 13), and (d) most frequently used metacognitive strategies from the think aloud interview (Guetterman et al., 2015). There was some overlap in the metacognitive strategies participants indicated they used the most as reported in the PMI and the strategies the participants were observed using the most during the think aloud interview. All participants had at least one metacognitive process that was listed as a most frequently used metacognitive process from both the self-report PMI and the think aloud interview observations (shown in italics in Table 14). For four of the seven participants, information management was the process that was prevalent in both measures. Information management is a process that the participants used frequently and demonstrated using information management in the way it is defined.

Table 14

Comparison of each participant's PMI and Think Aloud Interview

	PMI Results				Think Aloud Observations	
Name	**Mean**	***SD***	**Mode**	**Most Frequently Used Process**	**Total Counts**	**Most Frequently Used Process**
Lana	3.12	1.03	3	*info management* debugging evaluation	25	declarative *info management* planning
Judy	3.58	0.86	4	debugging conditional *info management*	41	monitoring declarative *info management*
Samir	3.19	1.17	3	conditional *debugging* planning	34	info management *debugging* monitoring
Catherine	4.27	0.83	5	*info management* evaluation debugging	19	planning *info management* monitoring
Aaron	3.50	0.76	4	*declarative* conditional debugging	84	monitoring *declarative* planning
Jessica	3.81	0.85	4	*planning* declarative *info management*	24	*info management* *planning* conditional
Ellie	3.65	1.23	5	debugging *conditional* procedural	40	info management *conditional* monitoring

Note: Italics added to emphasize overlap.

The PMI average for debugging, using strategies or seeking help to fix an error, did not align with the coding of the think aloud interview. Six of the seven participants indicated on the PMI that debugging was one of their top three most used metacognitive strategies, but this was not reflected in the think aloud interview coding. The context of the think aloud interview may have been the reason for the lower frequency of debugging. While some of the participants did ask clarifying questions as a way of debugging during the think aloud interview such as “V equals vo, Ah, is that the original, v initial?” (Aaron) and “Wait, does this mean I only have to answer one of these” (Samir), it is possible that they did not feel comfortable asking me the same questions they would pose to their teachers or peers. It is also a possibility that participants did not have access to the materials they normally use when engaging in a debugging strategy such as textbooks, notes, peers, and internet searches. Lana noted at one point when she was unable to solve one of the problems, “Like, maybe if I had my notes, I'd be able to answer this question, like accurately.” The list of equations was frequently reviewed as a debugging strategy. It is possible that participants would have used more debugging strategies if they were allowed to use other resources while solving the problems.

Total counts of metacognitive statements (shown in Table 13) are helpful to gather high-level trends among the participants, but there is more to how a student uses metacognition than the frequency of their metacognition use. Frequency counts do not indicate the quality of the metacognitive statement nor how well the participant used their metacognition. For instance, Aaron had the most instances of metacognition with 84 total statements coded while Catherine had the fewest with only 19. Aaron only answered one problem correctly while Catherine answered three correctly. The frequency of metacognition is not an indicator of number of problems solved correctly. The cases for each participant will describe context and quality of metacognition, going beyond the frequency counts.

Dissatisfaction. The think aloud interviews were reviewed for statements where the participant expressed dissatisfaction with their understanding. Dissatisfaction was categorized in two ways. Statements were categorized as internal dissatisfaction when the statement represented participant dissatisfaction with their understanding of the physics concepts needed to solve the problem. Statements were categorized as external dissatisfaction when the statement represented participant dissatisfaction with their understanding of the information given in the problem. Once statements of dissatisfaction were identified, participant activities while problem solving were coded and recorded for before and after the statement of dissatisfaction. Appendix I contains the full list of dissatisfaction statements as well as a description of what the participant was doing prior to and after their statement.

In total, 51 statements of dissatisfaction were made by the seven participants. Each participant made at least one statement expressions dissatisfaction, as shown in Table 15, with an average of 7.29 statements per participant (*SD* = 6.58). Aaron had the largest number of statements of dissatisfaction with this understanding with 19, and Jessica had the least with only one statement. This means that Aaron was more likely to catch his mistakes or be unhappy with his work than Jessica.

Table 15

Summary of Participants' Statements of Dissatisfaction

Participant	Internal Dissatisfaction	External Dissatisfaction	Total Statements of Dissatisfaction
Lana	10	1	11
Judy	9	2	11
Samir	0	3	3
Catherine	0	3	3
Aaron	17	2	19
Jessica	0	1	1
Ellie	3	0	3

Of the 51 statements of dissatisfaction made by the seven participants, 39 of those statements were internal dissatisfaction as shown in Table 15. Participants were more likely to share dissatisfaction with their own cognition than the information provided for them. For example, Judy expressed her dissatisfaction with her own content knowledge when she said, "Yeah, I don't understand this one, so" while working on 1C. Aaron had the most internal dissatisfaction statements (17). The other 12 dissatisfaction statements occurred when the participants shared dissatisfaction with their understanding of the information given in the problem, external dissatisfaction. For example, Judy said of the wording of problem 2C:

> So, I'm kind of confused by this one because, when asked for what force of friction is required to keep the system moving, I'm wondering if it's asking for a specific type of force of friction or if its asking for a numerical value.

This statement does not indicate that Judy is confused about the concept of friction, but just that she is not sure of the desired format for the answer to that particular problem.

Samir and Catherine had the most external dissatisfaction statements with 3 each. Samir, Catherine, and Jessica all shared only external dissatisfaction. They did not share statements in which they were unhappy with their own understanding of the physics concepts. Further analysis of how the participants used their statements of dissatisfaction are in the cases that follow.

Problem Solving Style. Each participant had a unique way to approach and engage with the three problems, but overall, I interpreted patterns of how the participants solved the problems. I classified participants based on their approach to the physics problems in two ways. The first way explained how students proceeded through the problems. The second way explained if the participant used their conceptual and/or computational knowledge to solve the problems.

I categorized participants as either arrows or iterators based on the way they moved through the problems. Participants categorized as arrows moved straight through the problems, one at a time. Even if the participant was not fully satisfied with their answer, they moved on to the next problem once they had an answer. Participants categorized as arrows did not try to correct or rethink the problem after they gave an answer. On the other hand, participants categorized as iterators continued to rethink the problem and try it from a different angle when they were not fully satisfied with their answer or did not understand how to get to an answer. If an iterator could not find a satisfactory solution after reworking the problem, they would move on. On average, arrows gave more correct answers to the problems than iterators.

While working through the problems during the think aloud interview, participants shared ways in which they engaged their conceptual knowledge and computational problem solving skills. Conceptual problem solvers relied more on conceptual understanding and everyday experiences than equations and numeric solutions to help them solve problems. Computational problem solvers relied more on equations and numbers to solve problems than conceptual reasoning. Hybrid problem solvers use a combination of conceptual reasoning and computational problem solving to get to their answer. Participants categorized as hybrid problem solvers often use one to support the other. For example, a participant may use their conceptual understanding to help them understand and set up the problem before computationally solving for the unknown quantity. Table 16 shows which approach each participant took to solve the five individual problems and if they reached the correct answer. Most participants used different approaches across the five problems. Lana and Aaron were the exceptions with Lana using only conceptual approaches to solve the problems and Aaron using only computational.

Table 16

Summary of How Participants Cognitively Engaged with Each Problem

Participant	1B either	1C compute	2B compute	2C compute	3B compute
Lana	concept*	concept	concept	concept	concept
Judy	hybrid*	compute	compute	compute	compute
Samir	concept*	compute	hybrid	hybrid*	concept
Catherine	concept*	hybrid	concept	hybrid*	hybrid*
Aaron	compute	compute	compute	compute	compute*
Jessica	concept*	compute	compute*	hybrid	compute
Ellie	concept*	compute*	hybrid*	hybrid*	hybrid*

Note: * depicts the participant reached the correct answer to the problem

The problem that was most frequently answered correctly was 1B with six of the seven participants answering it correctly. This was the only problem that could be answered conceptually and the only participant who answered it incorrectly tried to solve it computationally. Problem 1C was answered correctly the least with only Ellie answering it correctly. In 1C, the participants seemed to struggle with the covert conceptual clues (see Table 8) given in the problem more so than the other problems. Judy and Jessica both shared that they felt that the problem did not give enough information to solve the problem with Jessica stating, “I don't, I feel like I don't have enough information for either of them to be able to make any progress.”

Ellie and Catherine provided the most correct answers to the problems, getting five and three correct respectively. Both Ellie and Catherine used different approaches to the problems, but most of their work took a hybrid approach. Lana, Judy, and Aaron each got only one answer correct. While Lana took a conceptual approach to the problems and

Judy and Aaron a conceptual approach, all three used their same approach for all five problems. The one exception to this was Judy's work on problem 1B which started as computational and ended as conceptual. The participants who used a variety of problem solving knowledge were more successful in answering the problems.

Table 17 displays the overall categorizations for each participant's problem solving approach. In addition, Table 17 shares how much time each participant spent in total on the three problems and how many of the five parts the participant answered correctly. On average, the participants spent a total of 24 minutes and 3 seconds (*SD* = 9 min 55 s) to complete all three problems, correctly answering an average of 2.14 (*SD* = 1.46) of the five parts. Not all combinations of possible problem solving styles were represented. Hybrid Arrows were most common, with three participants falling into that categorization.

Table 17

Summary of Participant's Problem Solving Style

Participant	Problem Solving Style	Time Spent on Problems (min, sec)	Number of Correct Answers (max 5)
Lana	Conceptual Arrow	12 min 38 s	1
Judy	Computational Iterator	20 min 9 s	1
Samir	Hybrid Arrow	29 min 44 s	2
Catherine	Hybrid Arrow	13 min 29 s	3
Aaron	Computational Iterator	38 min 38 s	1
Jessica	Computational Arrow	20 min 55 s	2
Ellie	Hybrid Arrow	32 min 53 s	5

Additionally, the Hybrid Arrow participants were more successful in answering the problems correctly. Participants who combined conceptual and computational knowledge to solve problems answered more problems correctly. Further, looking at Table 16, these participants did not always use hybrid approaches and were able to switch between using conceptual and computational knowledge based on the information provided in the problems. They did not use the same approach for each problem like the participants categorized as computational or conceptual problem solvers. The combination using conceptual knowledge and computational knowledge, both for single problems and across problem sets, is a more successful approach than using only one set of knowledge.

It is important to note that Tables 16 and 17 only reflect data collected during the think aloud interviews. Jessica did not provide an answer for problem 1C in her think aloud interview. After the think aloud interview Jessica returned to the problem on her own and solved the problem, writing out her reasoning along with her computational work. Since this work was done outside of the think aloud interview, I do not know how long it took Jessica to complete the work, nor do I know what resources she used to solve the problem. Because of those reasons, that work was not reflected in Tables 16 and 17. Jessica's decision to return to the problem will be further discussed in her case.

The next sections provide greater detail as to how each of the seven participants solved the three physics problems. These cases will highlight the metacognition, cognition, dissatisfaction, and problem solving style of each individual participants. The purpose of examining each individual is to give further context and examples of how the participants used cognition and metacognition while solving physics problems. Once the individual cases are explained, I will summarize and answer the two research questions.

Lana

Lana was an 18-year-old who identified as a female of two or more races/ethnicities. She took Physics as a first-year physics course her senior year of high school. While taking physics, Lana was also enrolled in pre-calculus.

Physics Metacognitive Inventory Results. In the PMI, Lana's average overall score was a 3.12 (*SD* = 1.03), indicating that she sometimes used metacognitive strategies while solving physics problems. Her average PMI score was the lowest of the seven participants. Lana responded in the PMI that information management and debugging were the two strategies that she would most likely use while solving problems as shown in Table 18. Table 18 shows Lana's average PMI score for each of the eight metacognitive processes. Because of the small number of items factored into each average, the range was added as an additional measure of central tendency. Observations from the think aloud interview aligned with the PMI scores in that Lana did use information management frequently, but there was misalignment in debugging. Lana did indicate that she would have normally engaged in debugging by looking at other resources when she noted, "Like, maybe if I had my notes, I'd be able to answer this question, like accurately." Lana's two lowest PMI scores came in procedural knowledge and comprehension monitoring which aligned with think aloud interview observations of Lana's problem solving.

Table 18

Lana's Average PMI Scores by Metacognitive Process

Metacognitive Process	Mean	Range
Declarative Knowledge	3.00	2 – 4
Procedural Knowledge	2.50	2 – 3
Conditional Knowledge	3.00	3 – 3
Planning	3.00	2 – 4
Information Management	3.75	2 – 5
Comprehension Monitoring	2.25	1 – 3
Debugging	3.67	2 – 5
Evaluation	3.50	3 – 4

Think Aloud Interview Results. Lana spent about twelve and a half minutes working on the three physics problems. In doing so, she answered one question, 1B, correctly. Lana did not engage in any computational problem solving while working on the problems. She used concepts and logic rather than numbers and equations. The problem that she answered correctly was a conceptual question. This aligns with the observation that Lana used the fewest instances of using problem solving strategies (25) with the majority of those observations being coded as reading (11) or planning (9).

Table 19 is a similarity matrix heatmap of Lana's problem solving and metacognitive statements. The heatmap shows the number of statements during Lana's think aloud interview that were coded as both a problem solving strategy (reading, planning, calculating, answering, and checking) and as a metacognitive strategy (declarative, procedural, conditional, planning, information management, comprehension monitoring, debugging, and evaluation). The heatmap included statements that were both double coded as a problem solving and metacognitive strategy as well as overlapping statements that included one of the two. The heatmap is color coded so that strategies with no co-occurrences are white, intersections with only 1 co-occurrence are yellow, mid-range co-occurrences are orange, and co-occurrences with the largest quantities are red. All but one of Lana's problem solving and metacognition co-occurrences were during the planning phase of problem solving. Lana had the most observations where she used problem solving planning with declarative or information management. This aligns with Lana indicating on the PMI that information management is the metacognitive process she us is most likely to use while solving physics problems.

Table 19

Similarity Matrix Heatmap of Lana's Problem Solving and Metacognition Statements

		Problem Solving				
		Reading	Planning	Calculating	Answering	Checking
Metacognition	Declarative	0	3	0	0	0
	Procedural	0	0	0	0	0
	Conditional	0	1	0	0	0
	Planning	0	1	0	0	0
	Information Management	0	4	0	0	0
	Comprehension Monitoring	0	1	0	0	0
	Debugging	0	0	0	0	0
	Evaluation	0	0	0	0	1

Cognition and Metacognition. For each problem, Lana started by reading the problem and underlining or circling key terms as she read the problem as shown in Figure 12. As she read the problem, she also clarified what assumptions were made in the problem. For example, in problem one, Lana stated, “Well, we don't know if the balls exactly the same, but I guess context we can assume it is.”

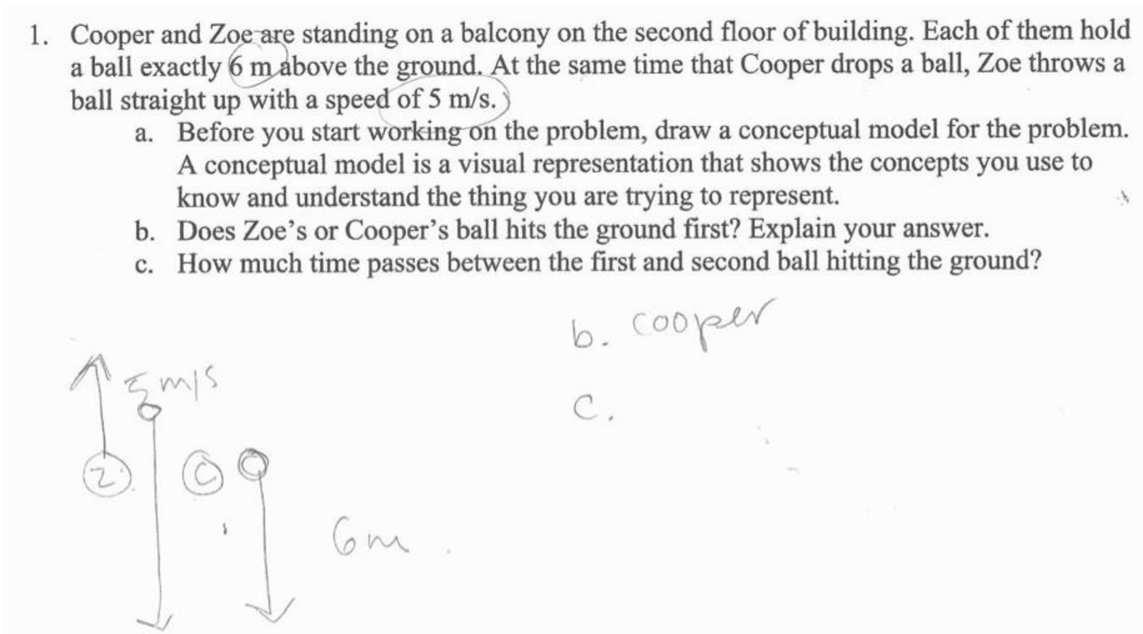

1. Cooper and Zoe are standing on a balcony on the second floor of building. Each of them hold a ball exactly 6 m above the ground. At the same time that Cooper drops a ball, Zoe throws a ball straight up with a speed of 5 m/s.
    a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.
    b. Does Zoe’s or Cooper’s ball hits the ground first? Explain your answer.
    c. How much time passes between the first and second ball hitting the ground?

Figure 12.

A sample of Lana’s work to solve physics problem one

When Lana got to the first question that required mathematics to solve it, 1c, she quickly realized that she did not remember the mathematical way to answer the question and shared:

> well, without actually remembering, like the actual equations, and how I would actually find the answer this I know that I have to take into account that the speed, the, the gravitational force pulling it back, the ball back down versus the gravitational force of the original like ball, just being dropped off, Cooper's ball, which is very conceptual and I'm confused by it already.

Lana did not attempt to use the equations given in the handouts, nor did she reference information from class. She continued the problem:

> (laughs) Sorry? Um. I'm not gonna be able to answer the actual question, because I don't know how long it, like, I'm not gonna get an actual answer, but I know that, I have to think about gravitational force as well as the actual, because like there's no force actually being put on Cooper's ball, other than the gravitational force like, it wasn't thrown up so there's no, like additional force being added. I forget the word for that words. Um. Where Zoe’s ball is being thrown up with a force and then now it has a gravitational force working on it. So, I think on the way down, they both have the same amount of force, depending on the weight of the ball. Um. It's just like it's starting at a different height so that's why the time is going to be different. (pause) Does that make sense?

Lana solved problems two and three in a similar way, noting that the questions asked for a mathematical answer, but giving a conceptual explanation instead. After reading problem two, Lana noted that “maybe if I had my notes, I'd be able to answer this question, like accurately.” Just like problem one (Figure 12), Lana did not show any work on her paper for problems two and three beyond circling key words in the problem and drawing a conceptual model.

When working on the problems, Lana’s tone made her seem confident in her decisions to answer conceptually instead of using mathematics and with her final answers. But during the process of thinking through her answers, she seemed to second guess herself. She did not feel that her conceptual answers were enough. In problem one, she explained, “I'm not gonna get an actual answer, but I know that…” Lana continually shared her feeling that her conceptual answers were not the “actual physics work that needs to be done there,” even though she used many physics concepts, and used them correctly, in her explanations. She further explained this in the follow up interview question:

> I knew that the ball, like Cooper's ball would hit the ground first because not because of the actual physics behind it, but because of my general knowledge of the world, and I knew that that ball is gonna hit the ground first.

Lana sees her everyday experiences and prior knowledge separate from her academic physics knowledge.

There were two instances to note in which Lana was able to use her metacognitive statements in a productive manner, furthering her understanding and helping her answer the questions. In problem two, as Lana finished question 2B (a block without friction) and started reading 2C (a block with friction), she realized that she made a mistake in her reasoning for 2B, “I see what I did here” and corrected herself while explaining 2C in terms of 2B. This is an example of Lana using her dissatisfaction to correct and learn from her mistake. In doing so, she was monitoring her comprehension and debugging her answer for 2B. In problem three, Lana was not sure how to approach the problem. She decided that she had “to figure out what these diagrams are telling me” before she could eliminate possible answer choices. While other participants also took the approach of eliminating answer choices for 3b, Lana was unique in that she combined test taking strategies with physics conceptual understanding to eliminate possible choices rather than using mostly test taking strategies to eliminate choices. For example:

> I think the net force is different for all of them. So I'm gonna say that it's not the last three thingies. And then I have to explain that, but. (laughs) See, I think the net force, the smaller the object is and the greater the velocity, the greater the net force is going to be. (pause and mumbles I think it what I?) So, I'm gonna now put them in order.

Lana used the size of the radius and speed quantities given in the figure to reason through her answer.

Lana was able to combine her cognition and metacognition to give an answer to the problems, even though, for many of the problems, she knew that she was not giving the correct answer since she was giving a conceptual answer when a numeric answer was expected. Most of her cognition occurred early in the problem solving process (reading and planning) which was mirrored in the metacognitive strategies she used the most (declarative, planning and information management).

Dissatisfaction. Lana expressed dissatisfaction eleven times during her think aloud interview with multiple statements shared about each of the three problems. All of

Lana’s dissatisfaction statements were about her own understanding of physics, internal, except for one. In Lana’s only statement expressing external dissatisfaction, “What?” she engaged in debugging by asking for clarification on what problem 3B meant. Lana decided early in the think aloud interview that she would not be able to give computational answers, “I'm assuming there's actual physics work that needs to be done there. (laughs, pause, puts hand on face/chin) Um. (sigh) Oh, okay, well, without actually remembering, like the actual equations, and how I would actually find the answer this” and would only give conceptual answers to the problems, “I’m not gonna get an actual answer.” In doing so, she did not use the equation sheet as a debugging tool as other participants had.

Many of Lana’s statements of internal dissatisfaction not only share that she is not clear of the physics concepts needed to answer the question, but they also share her disappointment with herself in not knowing. For example, after reading problem two she commented, “Uh, working on physics problems after this one really tells me how little I retained the information I learned in class. (laughs) Like, maybe if I had my notes, I'd be able to answer this question, like accurately.” The dissatisfaction statements that also shared her disappointment with her lack of understanding, for example, “I’m confused by it already,” did not lead to engagement in other metacognitive processes.

Lana did have one statement, “I see what I did here,” where she noticed a mistake in her explanation for problem 2B while she was reading problem 2C. This statement engaged Lana in the evaluating metacognitive process, checking and correcting her answer to 2B before moving on to finish problem 2C. This was the only internal dissatisfaction statement of the 11 total that prompted Lana to rethink or change her problem solving process. In the other 10 dissatisfaction statements, she either continued with her previous work or moved on to the next problem. Lana did not try to change her understanding, nor did she try to use a different set of knowledge to understand the problem. Lana did not appear to use her dissatisfaction to further the process of conceptual change.

Problem Solving Style. Lana was a conceptual arrow problem solver. She used conceptual understanding to explain the problem instead of giving a numerical answer as requested by the question. In doing so, she quickly moved through the problems, spending the least amount of time of all seven participants on the problems. The majority of Lana's metacognitive use occurred early in the problems solving process in the planning stage. And Lana used her statements of dissatisfaction to mostly share internal dissatisfaction. Only twice did she act on her dissatisfaction by changing her thought processes or debugging.

Judy

Judy identified as an Asian female. She was 16 years old when she took Physics as a first-year physics course her junior year of high school. Judy was also enrolled in AP Calculus AB during her junior year.

Physics Metacognitive Inventory Results. In terms of her self-report of physics metacognitive strategies, Judy's average PMI score was 3.58 (*SD* = 0.86), indicating that her perceived frequency of using metacognitive strategies was between sometimes and usually. Judy reported in her PMI that she was most likely to use debugging, conditional knowledge, and information management. All of Judy's average scores for the individual metacognitive processes are above 3.50 except for comprehension monitoring which was a 2.25. This does not align with the think aloud interview observations as comprehension monitoring was one of the more frequently observed metacognitive processes. Judy monitored her comprehension more frequently in the think aloud interview than she anticipated she would in the PMI.

Table 20

Judy's Average PMI Scores by Metacognitive Process

Metacognitive Process	Mean	Range
Declarative Knowledge	3.50	3 – 4
Procedural Knowledge	3.50	3 – 4
Conditional Knowledge	4.00	4 – 4
Planning	3.60	2 – 4
Information Management	4.00	4 – 4
Comprehension Monitoring	2.25	2 – 3
Debugging	4.67	4 – 5
Evaluation	3.50	3 – 4

Think Aloud Interview Results. In the 20 minutes Judy spent working on the three problems, she provided answers for two of the five parts, correctly answering the conceptual problem 1B. Judy was observed using problem solving strategies on 33 occurrences. The majority of those observations were of Judy reading the problem (16) or planning (15). Although Judy attempted to use computational methods for all of the problems, she did not complete any calculations, nor did she check any of her answers.

While declarative knowledge was one of Judy's more frequently used metacognitive strategies, she only used it once while also using problem solving strategies as displayed in her similarity matrix heatmap in Table 21. All but one of Judy's problem solving and metacognitive strategy co-occurrences happened when she was in the planning stage of problem solving. Planning and information management were the metacognitive processes she most frequently used during the planning stage of problem solving.

Table 21

Similarity Matrix Heatmap of Judy's Problem Solving and Metacognition Statements

		Problem Solving				
		Reading	Planning	Calculating	Answering	Checking
Metacognition	Declarative	0	1	0	0	0
	Procedural	0	1	0	0	0
	Conditional	0	1	0	1	0
	Planning	0	5	0	0	0
	Information Management	0	6	0	0	0
	Comprehension Monitoring	0	3	0	0	0
	Debugging	0	1	0	0	0
	Evaluation	0	0	0	0	0

Cognition and Metacognition. Judy started each problem by reading the information provided and then reading the first question. She would then try to use the numbers given in the problem to find an appropriate equation to solve the problem. Judy was very concrete in terms of what was "given to" her by the problem. She stated that "they didn't give me a velocity for Cooper" even though the problem stated that "Cooper drops a ball" indicating that the initial velocity for Cooper's ball was zero. Additionally, she did not conclude that the acceleration for both balls in problem one was the acceleration due to gravity since the balls were in free fall, stating "I also don't have acceleration." Unlike other participants, Judy did not try to solve for or find the information that she was missing to solve the problem. She only worked with values written in numeric form.

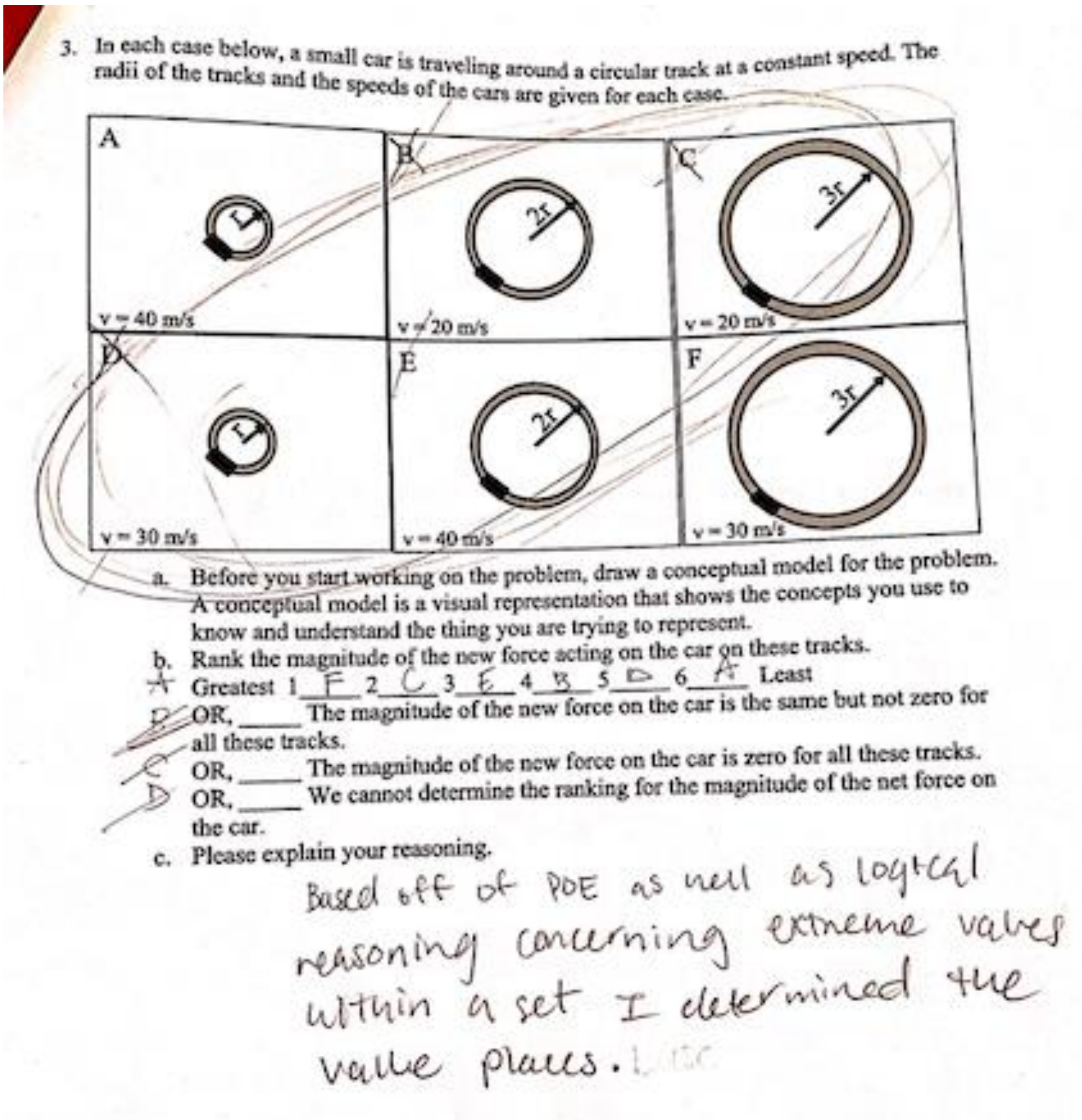
Judy worked on one part of the problem at a time. When she did not understand how to do question 1B, she decided "I'll move on to C, and I'll come back to B and see if I can solve it by then". Judy was unable to answer three of the four questions asked in problems one and two, but she looped back to them after doing problem three, sharing "I'm gonna go back and see if I can try to solve the other ones. Most likely won't be able to, so we can try." Judy iteratively worked through the questions, coming back to the questions she did not understand multiple times. Despite the multiple attempts, she was unsuccessful in giving an answer to three of the five questions.

Judy was more successful at answering problem three than problems one and two, but the strategies she used to get to an answer were test taking strategies, not physics problem solving strategies:

> So there are multiple options here almost like a multiple choice. I'm going to labeled it for myself. So, it's A for the first option, B for the second option, C and

D. Just so it’s, I can see it, and I can see, like, which one I want to cross out, if it doesn't make sense to me.

She did recognize that problem three was a circular motion problem, but that was the extent of the physics content knowledge she used to reason through to get her answer. She treated the problem as a multiple-choice problem, labeling the options A, B, C, and D as shown in Figure 13. She then used reasoning “based off of process of elimination as well as logical reasoning, um, concerning, um, extreme values within a set. I determined the value places based, or wait no. I determined the value places”. Similarly, when Judy gave her answer to 1b, the only other problem she gave an answer to, it was “a general answer based on logical reasoning” with little physics conceptual understanding used as part of her logic.



3. In each case below, a small car is traveling around a circular track at a constant speed. The radii of the tracks and the speeds of the cars are given for each case.

a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.

b. Rank the magnitude of the new force acting on the car on these tracks.

Greatest 1 F 2 C 3 E 4 B 5 D 6 A Least

OR, _____ The magnitude of the new force on the car is the same but not zero for all these tracks.

OR, _____ The magnitude of the new force on the car is zero for all these tracks.

OR, _____ We cannot determine the ranking for the magnitude of the net force on the car.

c. Please explain your reasoning.

Based off of POE as well as logical reasoning concerning extreme values within a set I determined the value places.

Figure 13.

A sample of Judy's work to solve physics problem three

Judy tried to solve each of the five problems using a computational solution using numbers and equations. When she was unable to computationally solve the problems, she left three unanswered and used logic to solve the other two. Before deciding to leave the three problems unanswered, she did return to try them again. Since she was unable to find an equation to solve the problems, Judy spent most of her time in the reading and planning problem solving processes and declarative and comprehension monitoring metacognitive processes.

Dissatisfaction. Judy had 11 statements expressing dissatisfaction distributed across the three physics problems. Nine of the statements were expressing internal dissatisfaction while two expressed external dissatisfaction. She was more dissatisfied with her lack of understanding than she was with the information given to her in the problems. When Judy was confused about the information provided, “So, I'm kind of confused by this one because, when asked for what force of friction is required to keep the system moving, I'm wondering if it's asking for a specific type of force of friction or if its asking for a numerical value,” she did not ask for clarification.

Judy was not able to give computational answers to the problems as she intended to, and most of her internal dissatisfaction statements reflect this. For example, after trying to choose an equation to solve problems 1B and 1C, Judy explained, “Well, I'm also not sure how to do that either. Because a lot of these, er, some of these equations I haven't seen before.” Judy had similar difficulties with problem two, stating, “I don’t think I know how to solve this one either.” With the exception of problem 1B, in which she started with a “logical” solution before trying to solve it computationally, Judy did not give conceptual explanations to the problems when she could not solve with equations. As she looked through equations, she was looking at them based on what she was given in the problems, not based on the underlying physics concepts. If she did not find an appropriate equation, she would move on.

Following four of Judy's dissatisfaction statements, she decided to move on to the next problem. While working on problem two, Judy explained, "I can't figure out what the quantitative and I, I don't really have any other options to solve it, for now I would just probably (short pause) leave it blank and then come back to it." Judy did return to problems one and two at the end of her think aloud interview as she had planned. After quickly looking over the problems and the equation sheets one more time, she decided that she was "confident in myself enough to know that I would not be able to solve this problem." She showed a combination of being dissatisfied with her understanding and feeling good enough with her work. Her willingness to go back and rethink the problems may have been the evidence of her starting the conceptual change process.

Problem Solving Style. Judy was a computational iterator problem solver. She attempted to find an equation to solve for the unknown based on the numbers overtly given to her in the problem. If she could not find an equation to solve the problem, she would move on with the intention of coming back to the problems she was not able to initially solve after she attempted the rest of the problems. Using her iterative approach, but unable to find an appropriate equation to use for the problems, Judy used reading and planning problem solving strategies the most along with declarative and comprehension monitoring metacognitive statements

Samir

Samir was a 17-year-old who identified as an Asian male. He took Honors Physics as a first-year physics course his junior year of high school. In addition to Honors Physics, he took Pre-Calculus.

Physics Metacognitive Inventory Results. On the PMI, Samir's overall average of 3.19 (*SD* = 1.17) indicated that he felt he sometimes used the physics metacognitive strategies while solving physics problems with conditional, debugging, and planning being the strategies that he rated as using most frequently. While six of the seven participants had debugging as one of their top PMI scores, Samir is the only participant who also demonstrated frequent use of debugging in the think aloud interviews. Comprehension monitoring, declarative knowledge, and evaluation were the three processes that he scored the lowest on the PMI. Comprehension monitoring was one of the metacognitive processes that he was observed using more frequently in the think aloud interview. Samir used comprehension monitoring more often than he had scored himself.

Table 22

Samir's Average PMI Scores by Metacognitive Process

Metacognitive Process	Mean	Range
Declarative Knowledge	2.50	2 – 3
Procedural Knowledge	3.50	3 – 4
Conditional Knowledge	4.00	4 – 4
Planning	3.80	2 – 5
Information Management	3.50	3 – 4
Comprehension Monitoring	2.00	1 – 3
Debugging	4.00	2 – 5
Evaluation	2.50	2 – 3

Think Aloud Interview Results. Samir spent almost 30 minutes working on the three problems, getting two of the five parts correct, 1B and 2C. Samir was observed using problem solving strategies 51 times, with almost half of those occurrences (21) coded as planning.

As shown in Table 23, Samir had a wide range of overlap between his use of problem solving strategies and metacognitive strategies. Samir had at least one co-occurrence of problem solving and metacognitive strategies within each problem solving category. Declarative knowledge is the only metacognitive strategy that was not used in congruence with a problem solving strategy. This aligns with his PMI results as Samir indicated that he does not use declarative knowledge as much as the other metacognitive processes. The largest number of co-occurrences for Samir fell into the categories of problem solving planning and information management, both of which he indicated on the PMI that he "usually" used.

Table 23

Similarity Matrix Heatmap of Samir's Problem Solving and Metacognition Statements

		Problem Solving				
		Reading	Planning	Calculating	Answering	Checking
Metacognition	Declarative	0	0	0	0	0
	Procedural	0	2	0	1	0
	Conditional	0	0	3	0	0
	Planning	0	4	0	0	0
	Information Management	1	8	0	2	0
	Comprehension Monitoring	0	1	1	0	1
	Debugging	0	1	1	0	1
	Evaluation	0	0	0	0	1

Cognition and Metacognition. Samir started each problem by reading the problem and part A. He would then draw and label a diagram as shown in Figure 14. As he drew the diagram, he would reread the problem to ensure that he pulled out all necessary information. Samir also used the diagram to write down things that he wanted to remember later such as, "on the right side I'm gonna put g equals nine point, point uh eight meters per second squared just so I don't forget." As Samir would solve for different quantities, he would go back and update his diagram (Figure 14). Samir did not use the diagram as just a way to start the problem, but as a tool to help him throughout the problem solving process.

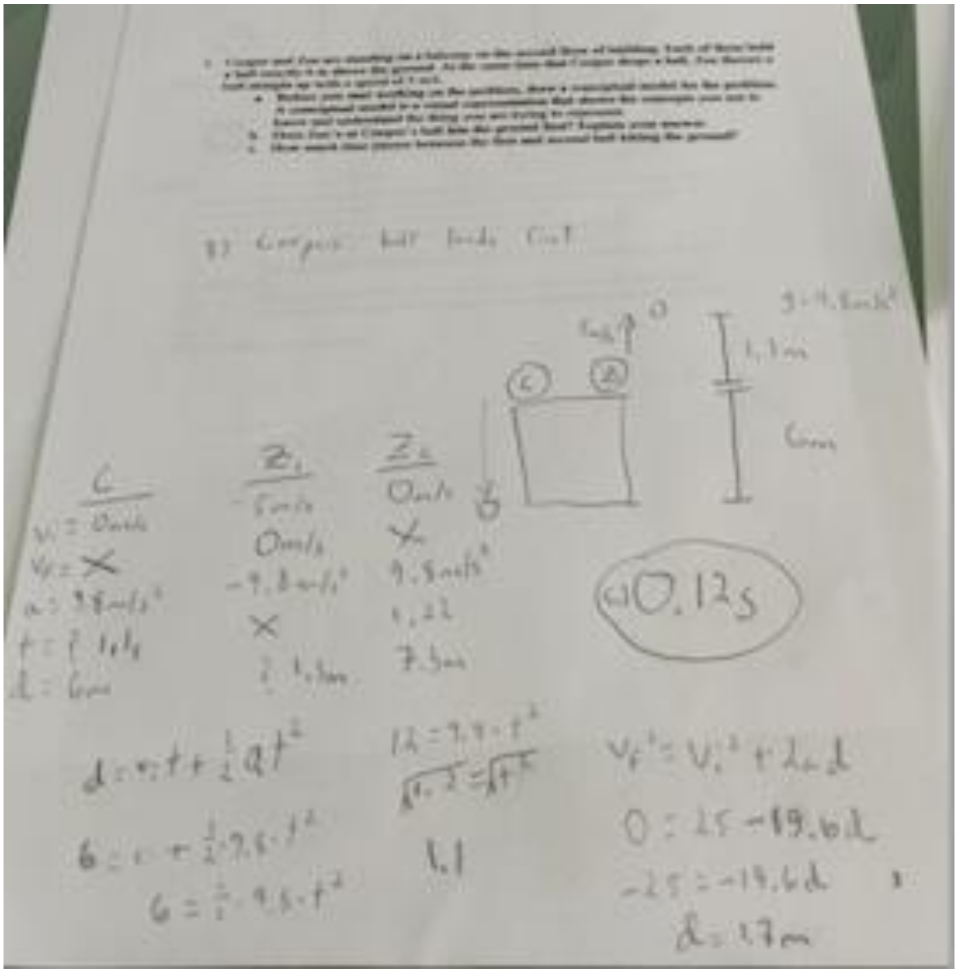


Figure 14.

A sample of Samir's work to solve physics problem one

After drawing and labeling his diagram, Samir would start the process of answering the questions. Samir used a combination of computational and conceptual problem solving strategies to solve the problems. On questions 1B and 3B Samir used all conceptual understanding and reasoning to answer the questions. He used mostly computational problem solving strategies for questions 1C and 2B, computationally listing knowns and unknowns, picking an equation, and then using many algebraic steps to solve for the unknown. And on question 2C, he started to talk his way through a computational solution to the question but realized he could just use his conceptual understanding, stating “Oh, wait, I'm not looking for the coefficient of friction. I'm looking at the force of friction, so I don’t have to answer that, I just have to say nineteen point six, ah it's Newtons.”

Samir used comprehension monitoring and evaluating throughout the process. Sometimes, Samir would let something remain wrong if it did not affect the outcome of the problem. For instance, he shared in the follow up question “I drew the normal force of by kilogram block the wrong way, even though that doesn't matter in the scheme of things, the neutral force, the normal force was supposed to be pointing upwards, not downwards.” He made similar statements about the use of significant figures while solving problems, “No, it's going to be one point four, four, nine, because the six six was messed up earlier. It shouldn’t be that much of an issue, because it would only be off a small decimal point.” Samir was able to monitor and catch his mistakes, but also judge if they were large enough mistakes that he would need to fix them.

Samir had a balanced approach to how he engaged in cognition and metacognition while solving the three problems. He used a combination of computational and conceptual knowledge to answer the physics problems. Additionally, Samir used metacognitive strategies within each of the problem solving steps.

Dissatisfaction. Samir had three statements of dissatisfaction; each statement was expressing external dissatisfaction in the form of a question. Samir’s statements were a means of debugging as all three of Samir's statements were a question asking for clarification on what was given or asked in the problem, not asking how to solve them.

In the first problem, after looking over the equation sheet, Samir was dissatisfied with the information given (external) on the equation sheet and asked for affirmation that he was correct in his understanding of the meaning of the variables "Is X to be distance by the way? For the equation sheet?...Okay. Just make sure. And initial velocity and final velocity. So final velocity is v and the initial was supposed to v o. Right?" When he used the equations, he used them in terms of variables he was comfortable with, not as they were given as shown in Figure 14. In problem three, Samir asked for clarification in his dissatisfaction twice, first asking "Wait, does this mean I only have to answer one of these" expressing external dissatisfaction with his understanding of the wording of problem 3B and later "Can you define the, the meaning of the word new force because that may have slipped my mind. I'm wrong" asking for clarification of the wording of the problem. Samir's last statement was sharing his internal dissatisfaction. All three of Samir's statements were a way for him to express dissatisfaction but also to engage in the debugging process by asking for help. Following all three of the statements of dissatisfaction, Samir continued to move forward in his work on the problem. While Samir did not show evidence of conceptual change, his willingness to ask clarifying questions to debug his dissatisfaction hints at the initial steps to engage in conceptual change.

Problem Solving Style. Samir was a hybrid arrow. He used his conceptual understanding to set up the computational problem solving, if computational solving was needed. Once Samir had his problem set up, he worked straight through the algebra to solve for the unknown. Most of Samir's instances of problems solving were in the planning stage, mirrored by the fact that he most frequently used information management, debugging, comprehension monitoring metacognitive strategies.

Catherine

Catherine identified as a White female. She was 15 years old when she enrolled in Physics as a first-year physics course during her freshman year of high school. Catherine also took Geometry her freshman year.

Physics Metacognitive Inventory Results. Catherine had the highest average PMI score of the seven participants, scoring a 4.27, SD = 0.83. She responded to more items on the PMI with a 5, always true of myself, than all the other participants. Information management and evaluation were Catherine's top two most frequently used metacognitive processes, scoring a 5, always true of myself, for all statements in those categories (Table 24). Catherine responded with either a 4, usually true of myself, or a 5, always true of myself, for all items except for those in comprehension monitoring. She indicated that she rarely (2) or sometimes (3) used comprehension monitoring, making it the only metacognitive process Catherine did not feel that she used regularly.

Table 24

Catherine's Average PMI Scores by Metacognitive Process

Metacognitive Process	Mean	Range
Declarative Knowledge	4.00	4 – 4
Procedural Knowledge	4.00	4 – 4
Conditional Knowledge	4.00	4 – 4
Planning	4.44	4 – 5
Information Management	5.00	5 – 5
Comprehension Monitoring	2.75	2 – 3
Debugging	4.67	4 – 5
Evaluation	5.00	5 – 5

Think Aloud Interview Results. Catherine was one of the fastest problem solvers, answering all three problems in thirteen and a half minutes. In doing so, she answered three of the five questions correctly, 1B, 2C, and 3B. While solving the problems, Catherine was observed using problem solving strategies 37 times, with the most instances of planning (13).

The similarity matrix heatmap of statements Catherine made during the think aloud interview that were coded as both a problem solving and a metacognitive strategy, Table 25, shows that the majority of the overlap occurred in the planning stage of her problem solving process, accounting for 13 of the 18 co-occurrences. Catherine rarely used metacognition while problem solving outside of the planning stage. The next highest occurrence were two uses of evaluation while checking her work once she was done with a problem.

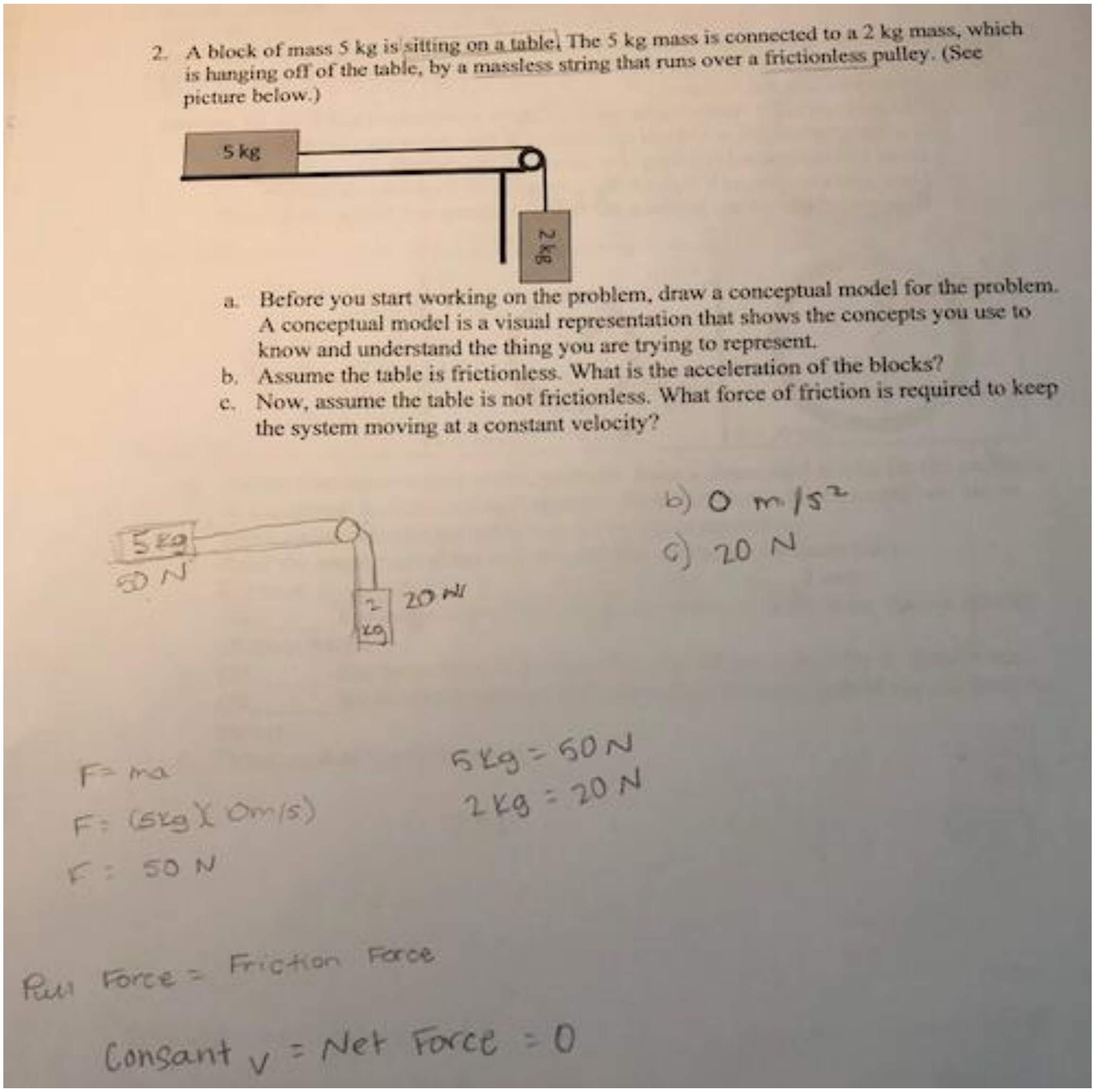
Table 25

Similarity Matrix Heatmap of Catherine's Problem Solving and Metacognition Statements

		Problem Solving				
		Reading	Planning	Calculating	Answering	Checking
Metacognition	Declarative	1	0	0	0	0
	Procedural	0	0	0	0	0
	Conditional	0	3	0	0	0
	Planning	0	4	0	0	0
	Information Management	1	4	0	0	0
	Comprehension Monitoring	0	2	1	0	0
	Debugging	0	0	0	0	0
	Evaluation	0	0	0	0	2

Catherine's PMI and think aloud interview results do not fully align. In the think aloud interview, Catherine was observed using planning, information monitoring, and comprehension monitoring the most and there was no observation of her using procedural knowledge or debugging. Catherine indicated on the PMI that she used all metacognitive processes frequently except for comprehension monitoring, so the high instances of comprehension monitoring and the lack of observations of procedural knowledge and debugging do not align with those self-report scores. Catherine used comprehension monitoring more than she recognized.

Cognition and Metacognition. Catherine started each problem by reading the problem. As she read the problem, she wrote down, underlined, and/or drew key ideas and concepts from the problem as shown in Figure 15. Catherine's drawing for problem 2B is very similar to the diagram given in the problem, with only two extra pieces of information added to it (see Figure 15). She noted, "I'm just gonna redraw it for my own sake. Sometimes that helps me."



2. A block of mass 5 kg is sitting on a table. The 5 kg mass is connected to a 2 kg mass, which is hanging off of the table, by a massless string that runs over a frictionless pulley. (See picture below.)

a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.
b. Assume the table is frictionless. What is the acceleration of the blocks?
c. Now, assume the table is not frictionless. What force of friction is required to keep the system moving at a constant velocity?

Figure 15.

A sample of Catherine's work to solve physics problem two

In the first two problems, where Catherine appeared confident in her content knowledge, she worked straight through the problem, explaining her thought process and reasoning. In these problems, she did not question her understanding of the physics concepts along the way, nor did she check her answers once she was finished. Her metacognitive statements for these two problems, 2 and 3, were coded as regulation of cognition statements falling into the planning and information management categories. Catherine's use of comprehension monitoring and evaluation all occurred in problem three.

While working on the problems, Catherine frequently mentioned or demonstrated using information she learned from class. When she started the first problem, Catherine stated:

> Okay, so I do remember from physics and my class that, um, throwing it horizontally doesn't affect the vertical movement. So if she were to throw it horizontally, they would of hit the ground the same time. But since they, since Zoe threw it up, straight up. Then they wouldn't hit it at the same time.

Catherine used that statement to springboard her work to answer questions 1B and 1C. On several occasions, it appeared that Catherine used equations and constants from memory rather than referencing the given equations and constants. For instance, Catherine used the equation $t = \sqrt{\frac{2d}{a}}$ to help answer questions 1B and 1C. She recalled the equation from memory rather than deriving it from the equation $x = x_o + v_o t + \frac{1}{2}at^2$, which is given on the equation sheet. Throughout the think aloud interview, Catherine used 10 m/s^2 for the acceleration due to gravity rather than 9.8 m/s^2 as it is defined on the equation sheet. Catherine's use of both the equation and the constant for acceleration were examples of her using her physics knowledge rather than the provided resources.

While solving problems, Catherine used a combination of physics conceptual understanding, mathematical understanding, and logic to answer the problems. For example, she used her understanding of the meaning of the acceleration due to gravity to answer problem 1C rather than using a physics equation:

> Gravity is, changes ten meters per second every second, but at a speed of five meters per second. So that means it would have to, if, if she threw it up, it would speed up. Er, slow down and go to zero at the apex and then speed up (pause) to go back to five meters per second. And all of it changes at ten meters per second, every second. And I'm gonna say that that adds up to one second. So, hers should be one second longer then. So there should be one second passes between the first and the second ball hitting the ground. That's gonna be my answer for that one.

In problem three, when she was less sure of her work, Catherine used mathematical reasoning to help her understand a possible way to solve the problem, "If I rank that, so they have the same denominator. Maybe that could be the answer."

Catherine used a blended approach to problem solving, using conceptual understanding and computational problem solving to solve the three problems. Her use of equations and constants not given on the equation sheet are evidence of her pulling from her prior physics knowledge. Most observation of her using metacognition were while she was in the planning stage of problem solving, early in the problem solving process.

Dissatisfaction. Catherine only had three statements of dissatisfaction, which occurred one after another while she was starting to work on problem three. She did not appear as confident in her understanding of uniform circular motion as she did with kinematics and Newton's laws. In all three statements, Catherine expressed dissatisfaction with her understanding of how to use the external information given to her. Prior to her first statement, Catherine was reading problem three. After reading the problem, she asked "Um, what do I need to know to determine the ranking of the magnitude (pause) of the net force?" This statement prompted her to conceptually review the information she needed to understand for the problem. Then she asked, "Why do I, why do I need to know the radius of the track?" This external dissatisfaction statement resulted in Catherine reviewing the equations and picking one to use. As she was calculating the acceleration, she again questioned the information given, "I don't know if I need to use that, do that with these. (pause while writing) Nine hundred r. Ok, I don't know if I'm going to need to use those. I don't think I will." After this final statement of dissatisfaction, Catherine continued with her calculations and confidently gave her final answer.

Two of the three statements of dissatisfaction were in the format of a question, but the question was directed at herself, not directed at me. Other participants, like Lana and Samir, asked questions when they were dissatisfied as a form of debugging, but Catherine did not. Catherine's statements seemed to not only express her dissatisfaction, but the self-questioning nature suggests that they were also a way for her to monitor her comprehension. And unlike some other participants, Catherine did not use her dissatisfaction as a way to go back and question her prior work; rather, she used it as a way to help her move forward. Catherine's dissatisfaction helped her to stop and review her understanding before moving on. While Catherine did not show evidence of conceptual change, reviewing her understanding is the possible start of conceptual change.

Problem Solving Style. Catherine was a hybrid arrow problem solver. She was a succinct and to the point problem solver, taking just over 13 minutes to complete all three questions. In solving the problems, Catherine employed both conceptual understanding and computational strategies. She did not rethink or reevaluate her work as she worked on the problems. This is evident in that most of Catherine's metacognitive processes were observed in the early stages of problem solving, especially planning.

Aaron

Aaron was a 17-year-old junior who was enrolled in Physics as a first-year physics course. He identified as a White male. In addition to Physics, he was taking Algebra 3.

Physics Metacognitive Inventory Results. Overall, Aaron indicated that he sometimes uses metacognition while solving physics problems based on his average PMI score of 3.50 (*SD* = 0.76). He responded in the PMI that he used metacognitive strategies declarative knowledge, conditional knowledge, and debugging most frequently, scoring each item in those categories as a 4, usually true of myself. Evaluation was the process that Aaron indicated that he used the least frequently. Planning was an interesting process for Aaron because he had a larger range of responses for those items compared to the other processes, ranging from a 2, rarely true of myself, to a 5, always true of myself. It seems that his use of planning is more strategy specific as compared to the other metacognitive processes.

Table 26

Aaron's Average PMI Scores by Metacognitive Process

Metacognitive Process	Mean	Range
Declarative Knowledge	4.00	4 – 4
Procedural Knowledge	3.00	3 – 3
Conditional Knowledge	4.00	4 – 4
Planning	3.80	2 – 5
Information Management	3.75	3 – 4
Comprehension Monitoring	3.25	3 – 4
Debugging	4.00	4 – 4
Evaluation	2.50	2 – 3

Think Aloud Interview Results. Of all seven participants, Aaron spent the longest amount of time, 38 minutes working on the three problems and had the largest number of statements coded as problem solving strategies, 85, and metacognitive statements, 84. Aaron answered 3B correctly and was the only participant who missed the conceptual problem 1B. Of the 85 observations of Aaron using problem solving strategies, the majority of them were in the early phases of problem solving: 20 were reading and 30 were planning.

As shown in Table 27, the similarity matrix heatmap shows that 54% of the total instances of co-occurrences of problem solving and metacognition were while Aaron was in the planning process of solving the problem. Aaron also had higher frequencies of co-occurrence for calculating with comprehension monitoring and checking with evaluation. Although Aaron did not have a co-occurrence for each possible combination of problem solving and metacognitive processes, each problem solving process and metacognitive process was part of at least one co-occurrence This means that Aaron used a variety of combinations of metacognitive and problems solving processes.

Table 27

Similarity Matrix Heatmap of Aaron's Problem Solving and Metacognition Statements

		Problem Solving				
		Reading	Planning	Calculating	Answering	Checking
Metacognition	Declarative	1	3	1	1	0
	Procedural	0	2	0	0	0
	Conditional	0	2	0	0	0
	Planning	1	6	1	0	0
	Information Management	1	6	0	0	0
	Comprehension Monitoring	1	6	6	1	0
	Debugging	1	1	0	0	0
	Evaluation	0	0	2	0	6

Aaron's think aloud interview observations did not fully align with his PMI scores. Declarative knowledge was indicated as a frequently used metacognitive process in both the PMI and the think aloud interview. Aaron was similar to other participants in that his PMI results indicate that comprehension monitoring is one of his least frequently used metacognitive processes, but he was observed using it frequently in the think aloud interview, accounting for more than a quarter of all of his metacognitive statements. Similarly, Aaron indicated on the PMI that he does not frequently use evaluation, yet he evaluated his work on eight occasions in the think aloud interview. Aaron monitored his comprehension and checked his work more often than he thought he did.

Cognition and Metacognition. For each problem, Aaron started by reading the problem and all parts associated with the problem. This is different from many of the other participants who did not read what was asked for part B until they completed part A. As he read the problems, he would underline parts of the problem he deemed important and cross out extraneous information as shown in Figure 16.

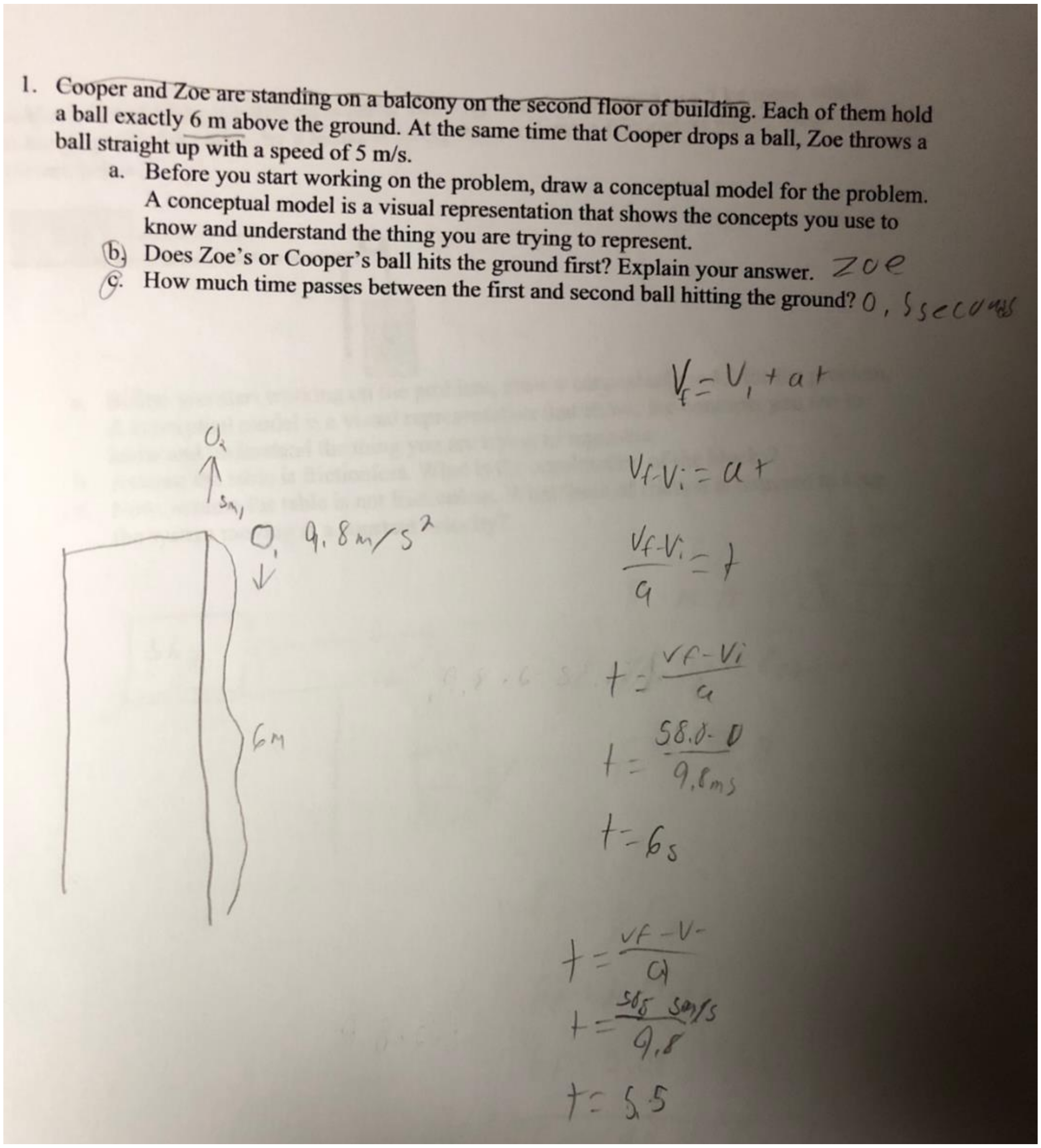

1. Cooper and Zoe are standing on a balcony on the second floor of building. Each of them hold a ball exactly 6 m above the ground. At the same time that Cooper drops a ball, Zoe throws a ball straight up with a speed of 5 m/s.
   a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.
   b. Does Zoe's or Cooper's ball hits the ground first? Explain your answer. Zoe
   c. How much time passes between the first and second ball hitting the ground? 0, 5 seconds

Figure 16.

A sample of Aaron's work to solve physics problem one

When starting to solve the problem, Aaron would consider what quantities were given in the problem and what unknown quantity he was asked to solve for. Based on that information, he would choose an equation to use. For instance, in problem one, Aaron started part B with:

> Okay, and then what are we looking for? Whose ball hits the ground first, so we're gonna need time. (pause to look at equation sheet) Yeah, velocity. Um. Hmm. Kay. What problems do we have that have time? V equals vo, Ah, is that the original, v initial?

Aaron used equations and the units associated with the quantities as his main information to determine how to solve the problem. When he was confused about how to use 9.8 in problem one, he used the units to reason through his decision:

> Well that wouldn't make sense. Why would we, I don't, you wouldn't be multiplying something. Nine point eight meters per second squared would have to be the acceleration, not the velocity because meters per second, you would have to multiply meters per second by meters per second to get, a squared. Right? So then that can't be the acceleration.

While Aaron used units to reason through problems multiple times, he mentioned that "my teacher always told me to write, ah, meters per second square next to it and I never did and I probably should, but I really, I don't see the point in it." Although he says he didn't see the point in including the units in his work, he used the units as information to help understand and solve problems.

When Aaron reached a point where he was confused, he would loop back to read the entire problem and look at the equation sheet for "a different way." Aaron continued to say "I can't remember any other equations and I don't see any other equations that could help me on the sheet.” Aaron did not share thinking about how the problem would play out in real life or what overarching concepts were involved in the problem as many of the other participants did. On problems one and two, he had an answer to part B, but was not satisfied with the answer. In both cases, he decided to go to part C, later returning to part B to rethink his work, “So the first answer does Cooper or Zoe’s ball hit the ground first? Um, Zoe’s, Zoe’s ball was throwing up in the air. Yeah, Zoe’s ball would hit ground first.” He even added thoughts from how he solved problem one when working on problem two: “and then I would think to myself oh, acceleration is nine point eight. Good thing you got that right on the first question. And you went through the whole thing not knowing.” Aaron did not see the parts of each problem as individual problems to solve, but rather as one big problem where one part helped him understand and solve the others.

Aaron frequently monitored his work and his thought processes. He once told himself, “Stop. What are you doing?” When Aaron checked his understanding, or checked his work, it was based on equations, units, and numbers. For example, when checking part of his solution for number one, Aaron thought out loud, “Nine point eight times six. That's not the right thing. Six. Then we get fifty-eight point eight, which seems like a very big number. Um, but that's the only thing that I have right now.” Aaron did not ask himself if the solution or his reasoning made sense, he only asked if the numbers, equations, or units made sense. With Aaron’s frequent monitoring and looping back to rethink the problems, he, by far, expressed the most metacognitive statements of any of the participants, having twice as many as the next highest amount.

Aaron relied mostly on computational knowledge while solving the physics problems during the think aloud interview. He frequently checked his understanding and work along the way, often leading him to question his work and rethink how he was going to solve the problem. Aaron continued to work and rework problems until he had an answer.

Dissatisfaction. Aaron shared the most dissatisfaction of all of the participants, sharing 19 statements of dissatisfaction while working on the three problems. Two of his 19 statements expressed external dissatisfaction. On the first one, "V equals vo, Ah, is that the original, v initial?" he asked for clarification on the meaning of the variables in the equations. The second time he expressed external dissatisfaction, he explained that he would have engaged in debugging if he were in a classroom situation:

> so wait you're looking for the acceleration of the blocks. (pause) Um, so, like block, I would probably ask my teacher, like the acceleration of both blocks. Like, would you want the acceleration of the two kilogram block? And then, what is the acceleration of the five kilogram block if the second block is pulling it? Or I would just sit here and I would think about, does that even make sense? What if they're the same thing and then I would probably just do the problem the whole way through. And figure it out, which is what I'm gonna do, I'm gonna figure out if, and if they're different, then I'll be like, okay, obviously it wants two different ones.

Although he did not ask for clarification following this moment of external dissatisfaction, he indicated that he would normally engage in the debugging process in similar situations.

Aaron used his dissatisfaction statements as a way to monitor his comprehension and prompt himself to look for other options. For example, he told himself “Wait, we're looking for, hold on... Okay. Yeah. So stop. What are you doing?” when he was working on problem one. In many cases, Aaron would reread the problem, or reestablish what quantity he was solving for, immediately following a statement of dissatisfaction, allowing him to reset and refocus his thought process. There were only two instances where Aaron decided to move on following his statement of dissatisfaction:

> But then I'm just mul, dividing and I'm just gonna get six. So that doesn't make sense. (sigh) So, then velocity final, when it’s, must be, no. (pause) So, ooo talking her out here, I feel like I'm just confusing myself and that I should just get an answer.

In both cases where Aaron decided to move on rather than address his dissatisfaction, this decision came after Aaron had made multiple iterative attempts to rethink the problem.

Aaron was often critical of himself in his expressions of dissatisfaction. On problem three, he noted of himself, “Finding, finding magnitude, that might have been the dumbest thing I've ever thought, or said. We're finding net force acting on the cars on these tracks greatest to least.” He seemed to align his dissatisfaction with his misunderstanding of the problems with intelligence, “I said sixteen thou, I wrote sixteen hundred and I promise you. I'm not, I’m not dumb.” Additionally, Aaron had the most emotional response to his dissatisfaction with his physics content knowledge of the seven participants. At one point, he had to remind himself to “Calm down here man.” Despite my multiple attempts to assure him that this was not a test, I was not judging him on whether he was right or wrong, Aaron continued to share that “And I'm, I'm stressing I'm sweating.” Aaron reminded himself throughout the process that “Calm down, this isn’t a test, you said that. I don’t know, I don’t know. I just need to calm down and do some physics.” Aaron both noted his dissatisfaction with himself and tried to reassure himself in these statements. At one point in the think aloud interview where he was confused about what the question was asking, Aaron commented that he would “would probably ask my teacher.” This statement, in combination with Aaron being frustrated at a personal level with this conceptual understanding leads to the belief that Aaron’s dissatisfaction could have been the start of the conceptual change process had he had resources to further debug his confusion.

Problem Solving Style. Aaron was a computational iterator problem solver. Of the seven participants, he spent the largest amount of time (38 minutes) working on the three problems relying mostly on equations to solve the problems. Aaron would continually circle back through problems until he had a good enough answer. With Aaron’s iterative nature to problem solving, he was observed using the most instances of metacognition, using metacognition in all parts of the problems solving process.

Jessica

Jessica identified as a White female. She was a 17-year-old junior enrolled in Honors Physics as a first-year physics course. She also took Pre-Calculus her junior year of high school.

Physics Metacognitive Inventory Results. On the PMI, Jessica indicated that she usually used metacognitive strategies for solving physics problems with an overall PMI average of 3.81 (SD = 0.85). Jessica responded that she was most likely to use planning and declarative knowledge strategies, followed by information management, procedural knowledge, and conditional knowledge tied for third. All of these processes tend to occur in the early stages of problem solving. Comprehension monitoring was noticeably Jessica's lowest scoring metacognitive process on the PMI and was the only process where she responded to an item with a 2, rarely true of myself. Jessica's other two lower scoring metacognitive processes were debugging and evaluation. This suggests that Jessica sees herself less likely to use metacognition in the later stages of problem solving.

Table 28

Jessica's Average PMI Scores by Metacognitive Process

Metacognitive Process	Mean	Range
Declarative Knowledge	4.50	4 – 5
Procedural Knowledge	4.00	4 – 4
Conditional Knowledge	4.00	4 – 4
Planning	4.60	3 – 5
Information Management	4.00	4 – 4
Comprehension Monitoring	2.75	2 – 3
Debugging	3.33	3 – 4
Evaluation	3.50	3 – 5

Think Aloud Interview Results. During the think aloud interview, Jessica spent 21 minutes working on the three problems and correctly answered 1B and 2B. After the interview was over, Jessica returned to problem one and reworked the problem. Her work and written out reasoning from the second attempt were not included in this analysis. Jessica was observed using a problem solving strategy 32 times. Reading (10) and planning (13) accounted for almost half of her problem solving strategy use instances.

The similarity matrix heatmap of Jessica's co-occurrences of problem solving strategies and metacognitive strategies, Table 29, again highlights her use of information management and planning. Jessica used metacognition along with each of the five problem solving processes at least once.

Table 29

Similarity Matrix Heatmap of Jessica's Problem Solving and Metacognition Statements

		Problem Solving				
		Reading	Planning	Calculating	Answering	Checking
Metacognition	Declarative	1	0	0	0	0
	Procedural	0	0	0	0	0
	Conditional	0	3	0	0	0
	Planning	0	4	0	0	0
	Information Management	2	5	0	1	0
	Comprehension Monitoring	0	0	0	0	0
	Debugging	1	0	0	0	0
	Evaluation	0	1	1	1	1

Jessica had strong alignment between her PMI scores and think aloud interview observations, more so than other participants. Information management and planning were in her most frequently used metacognitive process in both the PMI and think aloud interview. At the other end, comprehension monitoring, debugging, and evaluation were lower scoring for both. The one instance of misalignment is that Jessica noted frequent use of procedural knowledge in the PMI, but there were no observations of that metacognitive process in the think aloud interview. This overall alignment indicates that Jessica has a good awareness of her metacognitive use while solving physics problems.

Cognition and Metacognition. To start the think aloud interview, Jessica asked to use her own equations sheet that she brought to the think aloud interview. I asked that she not use her equations sheet and instead use the one I provided. As a result, before Jessica started the physics problems, she evaluated her resources by reading over the given equation sheet. Jessica started each physics problem by reading the problem and the question for part A. As she read, she underlined key words and numbers that she wanted to highlight for later as shown in Figure 17. Also demonstrated in Figure 17, Jessica either sketched a picture or used the given picture to label the given quantities and show the direction of movement. Jessica's next step was to look "through the equations to see which one I could apply."

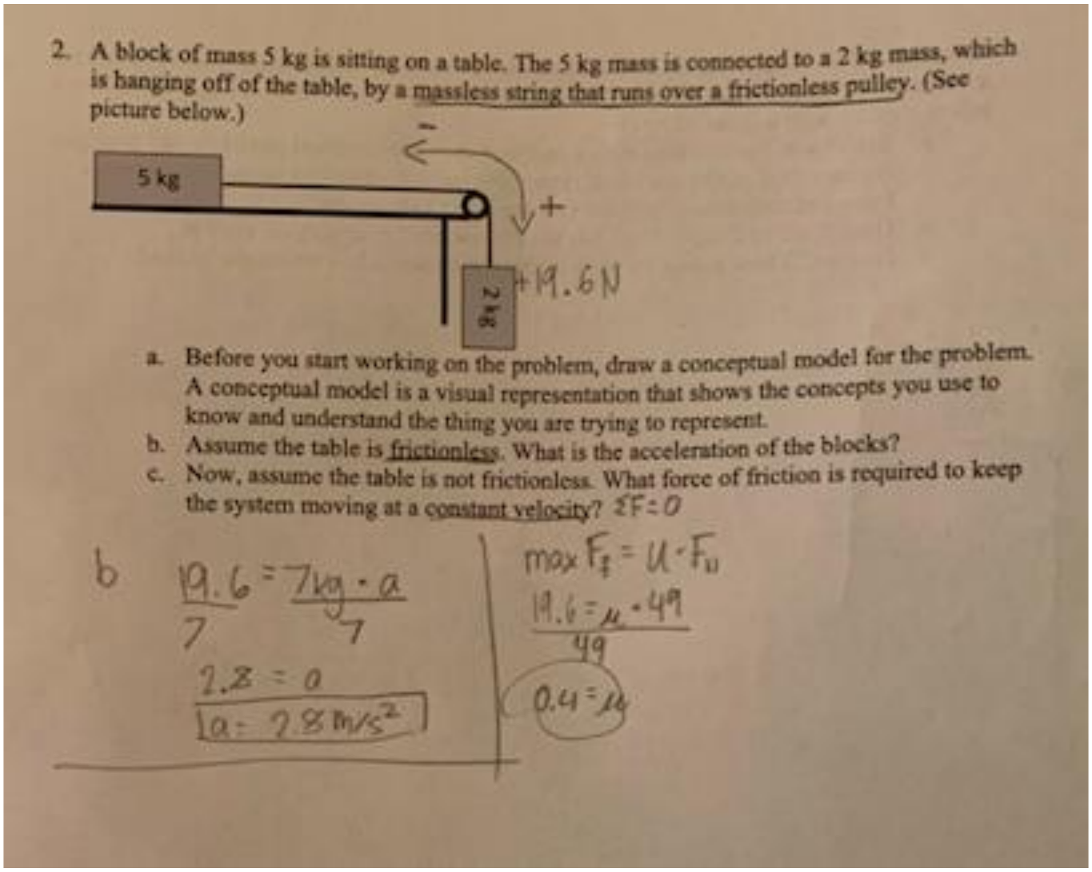


Figure 17.

A sample of Jessica's work to solve physics problem two

Jessica relied heavily on equations to decide how to solve the problems. She did weave some conceptual understanding into her reasoning, but the conceptual understanding she used was more definitional, such as "the five kilogram block has no friction, so it's not gonna resist it at all", rather than an understanding of a big idea. When she used conceptual understanding, it was for the purpose of picking an equation rather than understanding the scenario in the problem. And if Jessica could not find an equation that matched her list of givens, she would move on rather than give a conceptual answer.

When Jessica engaged in metacognition, it was mostly to plan how to do the problem or when she was managing the information provided. She only engaged in metacognition once each to monitor her comprehension and evaluate her solution. When Jessica did check her answer, “my coefficient of friction, which makes sense, because you always want something that's less than one,” her reasoning was more computational than conceptual. Even when she reached a problem that she could not solve, 1C, she explained that it was due to the fact that she was not provided enough information and did not question her understanding of the problem or her conceptual understanding, “I feel like I can't solve this because I don't have any timing on Zoe. I don't, I feel like I don't have enough information for either of them to be able to make any progress.”

Jessica used mainly her computational knowledge to solve the problems. Most of her engagement with metacognitive processes occurred early in the problem solving process, during the reading and planning stages. And when Jessica had a problem that she did not know how to solve computationally, she moved on rather than review the concepts needed for the problem.

Dissatisfaction. In the think aloud interview, Jessica only had one statement that expressed dissatisfaction, the fewest number of dissatisfaction statements of all of the participants. Taken in just the context of the think aloud interview, Jessica’s statement, “I feel like, I don't have enough information for this one, just because it doesn't tell me how long it's going up with a speed of five meters per second before it starts going back down again,” may not have been coded as a statement of external dissatisfaction. But given the fact that Jessica decided after the think aloud interview concluded to go back and redo the problem, this statement shares the beginning of that dissatisfaction process.

Prior to Jessica's statements, she was reading problem 1C. Jessica was dissatisfied with the amount of information the problem gave her, not her own content knowledge. After expressing her external dissatisfaction that the problem "doesn't tell" her enough information, she reviewed the equation sheet before deciding to move on to problem two.

With just the context of the think aloud interview. Jessica displayed a very low level of external dissatisfaction and no internal dissatisfaction. After the think aloud interview, Jessica decided to go back to the problem and rework the problem. When she emailed me her work samples, she included her new work for problem one, which included prose explaining her reasoning as shown in Figure 18. This indicates she possibly experienced internal dissatisfaction with her understanding of the problem. The thought process that Jessica had which led her to the decision to revisit the problem was not a part of the think aloud interview, therefore I do not have the evidence to make further evaluation of her dissatisfaction nor if it was a conceptual change shift.

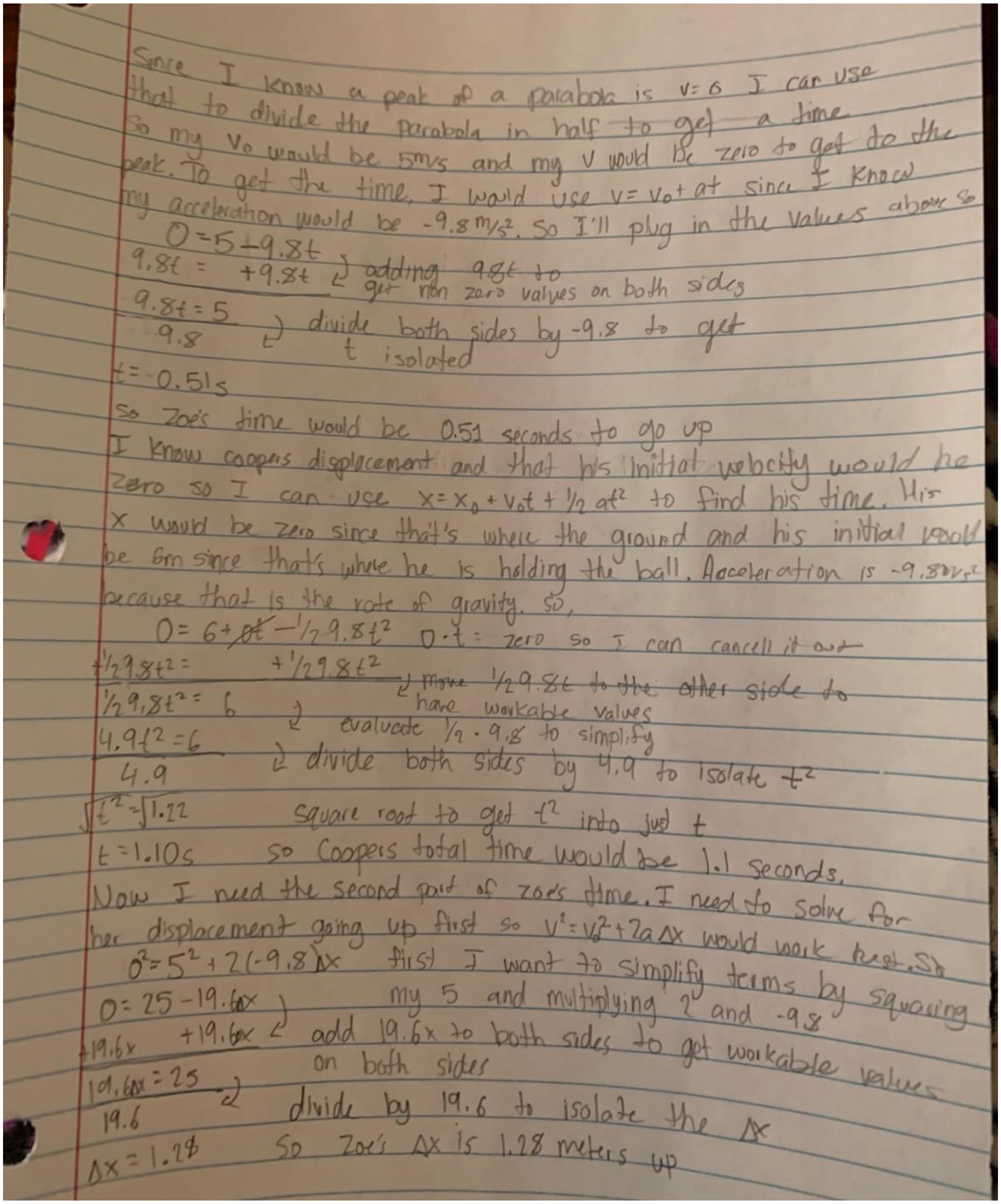


Figure 18.

A sample of Jessica's additional work done after the think aloud interview to solve physics problem one

Problem Solving Style. Jessica was a computational arrow problem solver. Jessica tried to solve the problems with equations, and when she could not find an equation to use, she would move on. In the think aloud interview, Jessica did not return to problems to rethink her work, nor did she try to answer questions conceptually when she did not find an appropriate equation. Jessica's use of metacognition was mostly in the early parts of problem solving, while reading and planning how to solve the problems.

Ellie

Ellie was a 17-year-old junior in high school when she enrolled in AP Physics 1 as a first-year physics course. She identified as a White female. In addition to AP Physics 1, Ellie also took AP Calculus AB and AP Statistics during her junior year.

Physics Metacognitive Inventory Results. Ellie's average PMI score, 3.65 *SD* = 1.23, indicates that she sometimes to usually used metacognitive strategies while solving physics problems. Her most used strategy as indicated on the PMI was debugging with the three knowledge of cognition processes, declarative, procedural, and conditional, all tied for second highest average score. Comprehension monitoring was her lowest scoring process. Ellie had more processes with larger ranges of scores than other participants suggesting that her use of metacognition is more strategy specific than process specific. For example, in planning, she scored a 1, never true of myself, on the item "Before solving a physics problem, I eliminate information in the problem that I don't need." and a 5, always true of myself, on the item "I think about what a physics problem is asking before I begin to solve it." In addition to those two planning items, she ranked one as a 2 (rarely), one as a 3 (sometimes), and one other one as a 5 (always). She responded to PMI items with a similar range for comprehension monitoring and evaluation as well.

Table 30

Ellie's Average PMI Scores by Metacognitive Process

Metacognitive Process	Mean	Range
Declarative Knowledge	4.50	4 – 5
Procedural Knowledge	4.50	4 – 5
Conditional Knowledge	4.50	4 – 5
Planning	3.20	1 – 5
Information Management	3.50	3 – 4
Comprehension Monitoring	2.50	1 – 3
Debugging	4.67	4 – 5
Evaluation	3.50	2 – 5

Think Aloud Interview Results. Ellie was the only participant to answer all five parts of the three problems correctly. In the 33 minutes Ellie was working on the problems, she was observed using problem solving strategies on 75 occasions and metacognitive strategies 40. Of the 75 instances of Ellie using a problem solving strategy, 35 of them were coded as planning.

Table 31 shows the similarity matrix heatmap of how Ellies problem solving statements co-occurred with her metacognitive statements. Ellie did not use metacognition while reading, and only used metacognition while answering a problem once. The largest quantity of co-occurrences were at the intersection of problem solving planning and information management.

Table 31

Similarity Matrix Heatmap of Ellie's Problem Solving and Metacognition Statements

		Problem Solving				
		Reading	Planning	Calculating	Answering	Checking
Metacognition	Declarative	0	0	1	0	0
	Procedural	0	1	0	0	0
	Conditional	0	4	2	0	1
	Planning	0	3	0	0	0
	Information Management	0	7	1	0	0
	Comprehension Monitoring	0	2	1	0	2
	Debugging	0	1	1	0	0
	Evaluation	0	1	0	1	3

During the think aloud interview, Ellie used information management, conditional knowledge, and comprehension monitoring most frequently. Procedural, debugging, and evaluation were the processes with the fewest number of observations in the think aloud interview. Ellie's think aloud interview observations did not fully align with that she indicated on the PMI. There was alignment with conditional knowledge and evaluation as conditional was a high scoring process and evaluation low for both the PMI and think aloud interview. Debugging and procedural knowledge did not align. They were both higher scoring processes on the PMI that had a lower number of observations in the think aloud interview. Comprehension monitoring was the opposite, because it was Ellie's lowest scoring process on the PMI but had a high number of observations in the think aloud interview.

Cognition and Metacognition. Ellie started the think aloud interview by reviewing her resources, reading over the equations that were given on the equation sheet. When she started a problem, she would read the problem, including the first question asked for that problem. Ellie would then use her conceptual understanding of the problem to choose her problem solving strategy and then draw a diagram to help her solve the problem. She was more detailed in the description of her strategy than other participants who decided on their strategy prior to starting the computations:

> Um, so I looked at the diagram right now. Recognize this as, I think we call it an Atwood machine… Um (pause) I remember how to do this. Okay. So the first thing I'm thinking is that, for if I should be doing a forces problem F equals m a or kinematics, but I've decided, I'm definitely gonna do it as a forces problem. Thinking Newton’s second law, force equals mass times acceleration or F equals m a. So I'm writing that down on my paper right now. F equals m a. And (pause) I’m, so now, I'm thinking oh, okay so this is what I would do for part A then for the conceptual model is I'm gonna draw a little dot presenting the five kilogram box, but I'm gonna do it basically as a free body diagram.

Ellie noted on the follow up question that in problems like problem one, she would not normally draw a picture, but she did because she was asked to draw a conceptual model:

> Like, for example, I use the free body diagram to aid me in, um, how I put the forces in the equation. But for me, like, the first thing I want to do, when I solve a physics problem is figure out my strategy then I'll use the free body. So, like, I like doing free body diagrams for forces problems. But, like, for kinematic, I wouldn't really need to do that, like I would just think about it in my head and draw my own visual picture in my head. Um. Same with the third one like, I wouldn't I mean, there was already a diagram given, so I wouldn't have like my own free body diagram or anything for the third one either.

She also noted that she regularly uses free body diagrams for forces problems like numbers two and three. When she drew her free body diagrams, she pulled from her conceptual understanding of how the problem worked to make sure that the length of the arrows reflected the magnitude of the force as shown in Figure 19. While she was drawing the free body diagram for number two, she shared:

> Oh. And I made sure that the normal force and the force of gravity the arrows are the same length, because the forces are acting with the same magnitude. So, it's not actually moving at all… Um, now this time, because I know that there is, um, acceleration and I know that like, logically, it's gonna accelerate with the two kilogram um mass falling down and that’s pulling the five kilogram mass right. Well, like, logically, speaking, I know that the gravity is gonna make the two kilogram mass fall down. So, I know that the force of tension is gonna end up being smaller than the force of gravity. And so my force of gravity arrow is just a little bigger.

These diagrams became the basis for the equations she used later to solve for the unknowns.

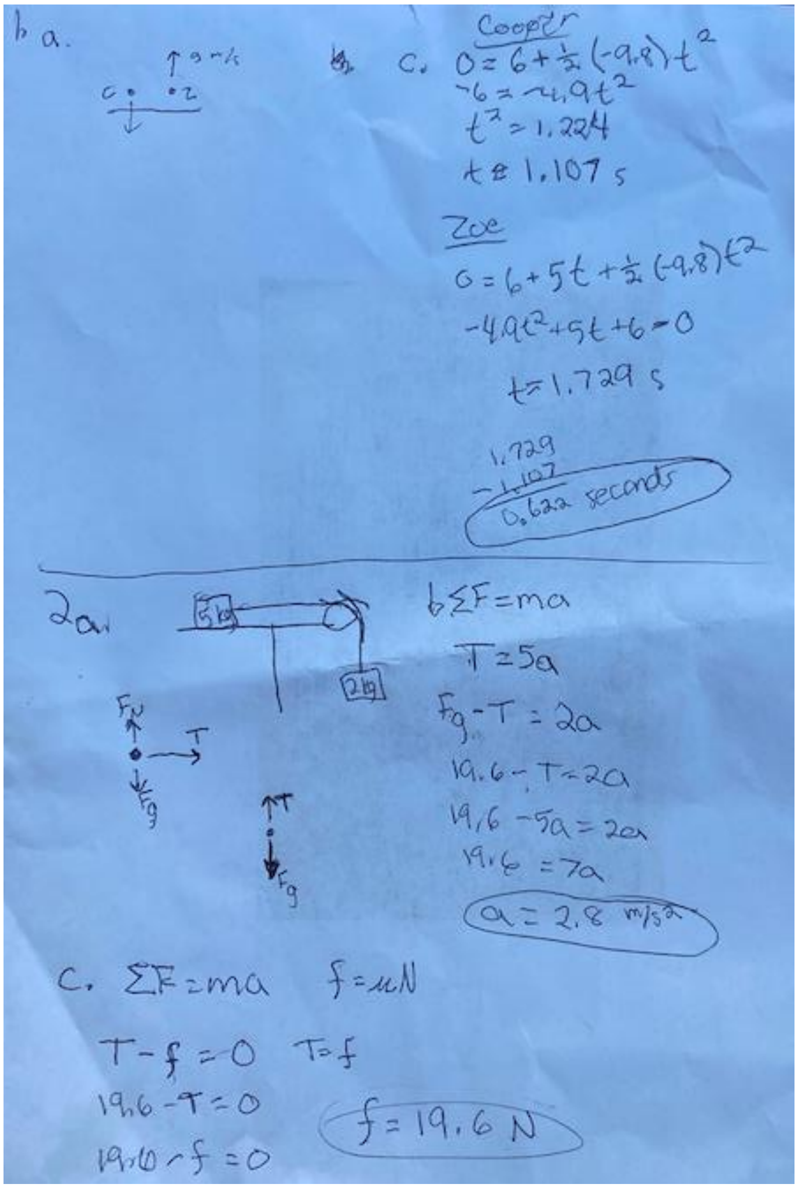


Figure 19.

A sample of Ellie’s work to solve physics problems one and two

While much of Ellie's metacognition use was in planning and information management, she also effectively used comprehension monitoring to aid her in her problem solving. For instance, while solving problem 2, Ellie stopped herself:

> Oh, wait. Okay. Hold on. Hold on. So I just realized a mistake. Oh, wait, no, never mind, it's fine. Never mind. I thought I made a mistake in, um, the sign in front of the six. I thought it should have been negative, but I realize that it's fine the way I.

When she stopped herself in problems one and two, she confirmed that she was correct and moved on. In problem three, however, Ellie was able to find a mistake and correct herself:

> Oh wait. Okay. Okay. Now I've changed. I changed my mind because, um (pause) it's a constant speed, which is true. However, the velocity is not constant because travelling in a circle, so it's constantly changing direction. So the velocity is not constant. So, um, I know the net force can't be zero. It has to have centripetal force, which is what I drew in part A. So I know that that answer's wrong for part B, it's not that it's zero for all these tracks.

Despite her frequently monitoring her understanding and work along the way, Ellie noted in the follow up questions that she is "not really a work checker." She considers checking her work re-running the numbers at the end of the problem and not monitoring her work and understanding along the way.

Ellie used a combination of conceptual and computational problem solving strategies to answer all of the problems correctly. She used metacognition in all aspects of problem solving except for reading the problem. The bulk of her metacognition coincided with the planning phase of problem solving.

Dissatisfaction. Ellie had three statements of dissatisfaction. All three internal dissatisfaction statements occurred while she was working on problem three. Ellie's dissatisfaction statements seemed to build upon one another, leading to her realization that she had misinterpreted the problem due to the difference between speed and velocity. As a result of her three statements of internal dissatisfaction, Ellie restarted her work for the problem, choosing a different method for answering the question.

Her first statement came as she was drawing her conceptual model after she had read the problem and analyzed the information given in the diagram for problem three:

> Um, ok, to be honest, this free body diagram is probably incorrect, the only force that I can think of right now, acting on the, um (pause) acting on the cars is just. I'm gonna draw a dot representing the car and I'm going to draw an arrow pointing inward, for um, the centripetal force. I guess. I don't know if that's right. (pause) Centripetal force, ok.

In this first statement, she started to question her understanding of the problem. After she chose an answer for 3B, she started to explain her reasoning in 3C. In the middle of explaining her reasoning, her dissatisfaction leads her to reread the problem, which is where she realizes her mistake:

> My reasoning that it's zero for all of these tracks is, it's said, in the description that the radii of the tracks and the speeds of the cars are, are no, it said traveling around a circular track at a constant speed. Oh wait. Okay. Okay. Now I've

> changed. I changed my mind because, um (pause) it's a constant speed, which is true. However, the velocity is not constant because travelling in a circle, so it's constantly changing direction. So the velocity is not constant. So, um, I know the net force can't be zero.

At this point, she decided that she needed to redo the problem, but she was again dissatisfied with her understanding because "Um. So now I'm gonna try to think. What, what (inaudible) okay. I'm trying to remember the equation used for, going back to the equation sheet." Ellie's initial dissatisfaction statement seemed to alert her that she was not sure of her current way of thinking about the problem, internal dissatisfaction, which led to her second dissatisfaction statement where she found her mistake and was able to correct her work. In this way, her dissatisfaction initiated her comprehension monitoring of the problem. Ellie's third dissatisfaction statement prompted her to engage in the debugging process by looking to the equation sheet to help her recall the equation she needed. Ellie's choices to consult the equation sheet and re-read the problem did not seem to be a response to being dissatisfied with her understanding like other participants had displayed, but rather to supplement her understanding. Ellie's three dissatisfaction statements worked together to get her to her final answer.

Problem Solving Style. Ellie was a hybrid arrow. Ellie used a combination of conceptual understanding and computational problem solving strategies to solve the three problems. With the exception of problem three, Ellie did not go back to rethink or reevaluate her work as she went along. Most of Ellie's observations of metacognition occurred while she was in the planning phase of problem solving.

Summary. Each participant demonstrated a unique approach to solving the three physics problems. This includes how they engaged in cognition and metacognition; how they expressed and used dissatisfaction; and their problem solving styles. Despite the uniqueness of the participants' individual approaches, trends emerged as to how high school physics students use cognition, metacognition, and dissatisfaction while solving physics problems. These trends will be discussed while answering the two research questions in the next two sections.

How do Current High School Physics Students use Cognition and Metacognition to Solve Physics Problems?

Overwhelmingly, participants displayed the most problem solving and metacognitive processes early in the problem solving process, particularly during the planning stage. The section to follow will go into more detail regarding the trends in the participants' use of cognition and metacognition while solving physics problems both individually and together. And in addition to considering physics concepts while solving problems, participants also shared thoughts about how (a) teacher influence and expectations, (b) problems as assessments, and (c) common sense and logic applied to their physics problem solving process.

Trends in Usage of Cognition and Metacognition

Cognition. While the seven participants each had a unique approach to solving the problems, there were trends in how they used physics problem solving and metacognitive strategies. Table 32 shows the total counts of statements coded for use of problem solving processes and metacognitive processes. Overall, there were 338 comments coded as a participant using a problem solving process. Forty percent of those instances of problem solving strategies being used were during the planning process, with the next highest problem solving process used was reading at 27%. The participants spent more time reading and planning how to solve the problem than they did calculating, answering, and checking their problem. This means that two thirds of the problem solving process occurred early in the problem solving process.

Table 32

Counts of Statements Coded for Each Problem Solving and Metacognitive Process

Problem Solving Code	**#**	**Metacognition Code**	**#**
Reading	93	Knowledge of Cognition	80
Rereading	35	Declarative	45
Planning	136	Procedural	10
Drawing Picture or FBD	19	Conditional	25
Arranging Information	44	Regulation of Cognition	187
Listing Knowns & Unknowns	41	Planning	40
Choose Concept or Equation	46	Strategy	35
Calculating	39	Allocating Resources	2
Answering	50	Goal Setting	2
Checking	20	Information Management	50
		Comprehension Monitoring	53
		Debugging	28
		Evaluation	16
Total	**338**	**Total**	**267**

Within planning, participants were observed arranging information, listing knowns and unknowns, and choosing a concept or equation at roughly equal frequencies. Drawing a picture or free body diagram had a little less than half of the observations as the other planning subprocesses. In the think aloud interviews, most participants would draw their diagram at the beginning of the problem, and then not come back to it while working on the problem. On the other hand, participants would frequently engage in the other three planning subprocesses multiple times while working on a single problem.

Reading was the second most frequently used problem solving process. Of the 93 occurrences, just over a third of those occurred when participants went back to the problem to reread the information given. This was frequently done when a participant was unsure of what to do, or to check if they had missed information. Participants also engaged in reading different ways. Some participants, like Lana, Catherine, Aaron, and Jessica, annotated while they read, while others, like Judy, Samir, and Ellie, did not.

The least used problem solving process was checking their answer. The participants checked their answers at the completion of the problem only 20 times out of the combined 35 opportunities that they had to do so. As will be explained further in the next section, participants were more likely to check their understanding during their problem solving process than to check their answer at the end.

Metacognition. Table 33 shares the average PMI for each of the eight metacognitive subprocesses for the seven participants. Because of the small sample size, mode and range are shared as additional measures of central tendency. The most common response to the PMI items asking participants how frequently they used 26 metacognitive strategies for solving physics problems was a 4, usually true of myself. As a whole, the participants saw themselves as frequently using metacognitive strategies while solving physics problems.

Table 33

Average PMI Scores by Metacognitive Process for All Seven Participants

Metacognitive Process	Mean	Mode	Range
Declarative Knowledge	3.71	4	2 – 5
Procedural Knowledge	3.57	4	2 – 5
Conditional Knowledge	3.93	4	3 – 5
Planning	3.77	4	1 – 5
Information Management	3.93	4	2 – 5
Comprehension Monitoring	2.54	3	1 – 4
Debugging	4.14	5	2 – 5
Evaluation	3.43	3	2 – 5
Total	**3.59**	**4**	**1 – 5**

The metacognitive process with the highest average on the PMI was debugging. With an average of 4.14 and a mode of 5, the participants indicated that they always use debugging strategies when they need help while working on a problem. Comprehension monitoring was the lowest average at 2.54, a mode of 3. Participant did not see comprehension monitoring as a strategy that they use frequently. Planning was the only strategy where the range of responses covered all five answer options, meaning the participants had a wider range of experiences and use of planning strategies. Conversely, participants responded to conditional knowledge items with the smallest range. All participants responded that they at least used the conditional knowledge items "sometimes".

In the think aloud interviews, participants engaged in more than twice as many regulation of cognition processes than knowledge of cognition process in the think aloud interviews as shown in Table 32. This meant that they were more likely to control and monitor their work than they were to share what they know about how to solve the problem. The top two processes used were information management and comprehension monitoring. This meant that the participants frequently used strategies to help them solve the problems and checked their understanding of the physics concepts as they were working on the problems. This is interesting because in the PMI (Table 33), information management was one of the top five strategies that participants noted they were more likely to use and comprehension monitoring was the lowest scoring strategy. The participants PMI results for information management matched those of the think aloud interview observations, meaning the participants were aware of their frequent use of strategies while solving problems. There was a misalignment between the participants' response to comprehension monitoring statements in the PMI and the think aloud interview observations. It is possible that the participants did not notice when they were monitoring their comprehension, or they did not realize how frequently they did so. Ellie alluded to this in her response to the follow up question:

> I don't know, I think that's all. I, I know I don't really check my work. Like, if it was a test, I would, um (pause) I don't know, I never really run the numbers again, but I would just look over it and make sure it makes sense again before I moved on to the next problem.

Ellie did not think making sure things made sense counts as "checking" or monitoring her work. She only saw recalculating the problem as counting as monitoring and evaluating her work.

Cognition and Metacognition Co-occurrences. A similarity matrix heatmap was used to show where in the problem solving process participants were using metacognition for all participants (see Table 34). The heatmap included statements that were both double coded as a problem solving and metacognitive strategy as well as overlapping statements that included one of the two. The heatmap is color coded so that strategies in which no co-occurrences were found are white, intersections with only 1 co-occurrence are yellow, mid-range co-occurrences are orange, and co-occurrences with the largest quantities are red. The heatmap emphasizes that two thirds of the occurrences where participants were using metacognition during the problem solving process happened during the planning stage.

Table 34

Similarity Matrix Heatmap of Problem Solving and Metacognition Statements for All Seven Participants

		Problem Solving				
		Reading	Planning	Calculating	Answering	Checking
Metacognition	Declarative	3	7	2	1	0
	Procedural	0	6	0	1	0
	Conditional	0	14	5	1	1
	Planning	1	27	1	0	0
	Information Management	5	40	1	3	0
	Comprehension Monitoring	1	15	9	1	3
	Debugging	2	4	2	0	1
	Evaluation	0	2	3	2	14

The planning problem solving process accounted for four of the five highest frequency co-occurrences (shown in red on Table 34). In general, the participants were more metacognitive in the beginning of the problems solving process, when they were setting up the problem: deciding what information was given to them and choosing what equation or concept to use. The intersection of planning and information management was the highest frequency with 40 of the 178 total co-occurrence observations. Additionally, planning was the only problem solving phase that had co-occurrences with all of the metacognitive processes. The planning phase of problem solving offered the most opportunity for participants to engage in metacognition.

Answering was the problem solving process where participants used metacognition the least with only nine co-occurrences. In most cases where a participant was answering, the participants simply stated their final answer without any extra explanation, "So a equals two point eight" (Ellie), which accounts for the low frequency of co-occurrences. If a participant went on to evaluate/check their answer, it was typically done in a separate statement.

Accounting for 23.53% of the co-occurrences, information management was the metacognitive process that was most frequently used along with a problem solving process. Information management was used in combination with all steps in problem solving except for checking. Until the point where they were checking their work, participants were choosing strategies to make them more successful.

With very close frequencies, procedural knowledge (7) and debugging (9) were the least used metacognitive processes in collaboration with a problem solving process. Participants did not state how they were going to do the problem while they were working on the problem, and when they did, they did so in the planning stage of problem solving. As discussed earlier, the low frequency of debugging may have been due to the environment of the think aloud interview. Participants may be more likely to debug in their normal physics classroom setting. When participants did engage in debugging, they were in the early stages of problem solving while they were reading, planning, and calculating.

In addition to the trends in how the participants used the different strategies, three themes emerged from the participants' cognition and metacognition in the think aloud interview. These themes, (a) teacher influence and expectations, (b) problems as assessments, and (c) common sense and logic, were each mentioned by multiple participants on numerous occasions. Each individual theme is further discussed below.

Teacher Influence and Expectations

While in the process of working on the three problems or when answering the reflective follow up question, all but one student mentioned their teacher. In these statements, the participant either mentioned something that their teacher taught them or what their teacher would want or expect them to do. Participants noted both problem solving strategies their teachers taught them and teaching strategies that helped them to be more successful in class.

Jessica, Samir, and Aaron all mentioned specific physics problem solving strategies their respective teachers taught. When reflecting on what she noticed about her problem solving at the end of the think aloud interview, Jessica said:

> I figure out problems the exact way my teacher taught me, which was to kind of look at what you have, and look where you need to be and kind of wiggle your way through that, whether it's going a little bit backwards to forwards or forwards to backwards.

This statement is reflective of the strategies Jessica did use while solving the three physics problems.

While Samir and Aaron mentioned problem solving strategies their teacher taught them or expected them to use while solving physics problems, they also explained how those methods either did not match their own problem solving or did not make sense to them. Samir first mentioned the dissonance between how he was taught and his own preference while solving a physics problem:

> What I've been taught because I'm also thinking I know I've been taught to, ah, isolate, you know, the variable first before plugging in numbers. Um, I personally don't see the, I personally prefer just plugging the numbers in and isolating from there. So, I'm just do what I would normally do, and just plug in the numbers.

Samir further reflected on this thought process in the follow up question stating:

> Well, my teacher always taught me, first like, organize your key variable set up because I know I noticed for the first problem I did it the way I would normally do it. And I was contemplating doing it the way that my teacher would do it. I realized that's not something I would do outside of a testing environment. So, I'm gonna stick to what I normally do, which is, you know, just plug in the numbers and solve for the variable instead of solve for the variable and then plug in the numbers. So that's one thing I noticed.

Samir changed the way he was solving the problems because he did not feel it reflected his way of problem solving; rather, he was mirroring his teacher's problem solving process. Additionally, Samir's statement shared that he solves physics problems differently on a test compared to how he solves physics problems for practice. This suggests that Samir sees two different purposes for problems: assessments and practice problems.

While solving the problems, Aaron shared how he was following the problem solving strategies that his teacher shared with him, but that he does not understand why he should use that strategy. When plugging numbers with units into an equation, Aaron says, “my teacher always told me to write, ah, meters per second square next to it and I never did and I probably should, but I really, I don't see the point in it.” In another problem, Aaron was redrawing a diagram that was provided on the problem and explained that is was “something that my teacher had us do all the time. She would just have this re, redo what was there. Um, and I don't, I still don't understand why. (laughs)” While both Samir and Aaron did not find value in or understand the strategies their teachers shared with them; Aaron continued to use those strategies while Samir chose to use his own strategy.

Participants also brought up teaching strategies that affected how they thought about the physics problems. Aaron commented at the beginning of the think aloud interview that he was comfortable with sharing his thoughts out loud because his teacher “would have us go up on the board, write them down, and explain to the class how we did it. So, this is like, second nature for me now.” Both Judy and Catherine made comments about how they rethought their approach to problems because either their teacher would not make the solution that easy, or their teacher tended to add trick questions. As they explained it, a trick question was one where the answer was not obvious or a question where they would need to read carefully to make sure they gathered all of the information correctly. This came up with Judy when she was stuck on a problem and was trying to use reasoning and the process of elimination to answer the physics problem. She noted, “I wouldn’t think it would be zero, because that's just kinda seems pointless as a question in general. Like, I wouldn't expect them to give me such an easy answer. So, I'm going to cross that one out." And later added, "that's never an option because that is a tricky one with easy way out for students like me, who don't know what's going on." Catherine's comment in the follow up question had a more positive spin on the trick question. She shared how her teacher's tendency to use tricky questions helped encourage her to "make sure I read each problem carefully and then, like, double checking my work, I guess."

And lastly, participants shared other ways their teachers helped them to be successful in class. Lana shared an interesting thought about how her teacher's more lenient assessment style helped her learn physics:

> and while I did very well in that class, it was mostly because it was very, like, it was a very easy class to pass because I had a very good table partner. We're very smart together. We worked well together and my teacher kinda just like, let us copy off of each other. So, (laughs) like, legitimately, we'd be taking a quiz and everybody in our little for like, four person table groups would just look at each other and be like, what'd you get? Is this like, are we all on the same page here? Okay, cool. That's fit (laughs) and such. But I think that honestly it made all of us a little bit smarter, because we all pay attention more and like helped each other.

Lana saw the collaborative nature of assessments as an integral part of her learning on physics. Aaron hinted at two occurrences that his teacher gave him scaffolded support than was provided for the three physics problems. While writing down the answer to a problem, Aaron stated, "One thirty three point three, three, three. Um, point three, three we'll just rounded to two decimal places in this one because it doesn't tell me how far to round and I don't wanna use sig figs because, I don't." suggesting that he is used to the problem or teacher telling him how many decimal places to use. In the follow up question, Aaron shared that he was not used to having so many equations to choose from, "on tests and stuff for like, in school, she gives us equation sheets and they usually only have the equations that we're using on them. So I feel like I tried to do that with this, and I don't know if I got them all right but I, I definitely tried to use process of elimination." The expectations, support, and scaffolding that the teacher provided were important aspects of the cognition and metacognition the participants shared in relationship to how they would approach the problems. Many of the cognitive and metacognitive strategies used by the participants in the think aloud interview were taught to them by their teachers.

Problems as Assessment

Four of the participants shared thoughts on how they would approach the problems if they were taking an assessment, rather than just working on the three problems. These comments included both how they approached the problems differently and what strategies they would use if they were stuck on a problem while taking an assessment. In total, eight excerpts from participant interviews mentioned an assessment situation.

Samir, Ellie, and Aaron shared during the follow-up question strategies that they use on an assessment that they do not normally use when solving practice physics problems. Samir commented that he solved problems using different steps than the method his teacher taught him, "And I was contemplating doing it the way that my teacher would do it. I realized that's not something I would do outside of a testing environment. So, I'm gonna stick to what I normally do." Samir shows more work and follows additional steps on an assessment to match his teacher's expectations but decided to do the problems for his think aloud interview the way he would "normally do" them, not the way he would on an assessment. Ellie shared that she would more carefully evaluate her work on an assessment than she did for her three problems because "if it's not like an exam, I'm not really a work checker." Both Samir and Ellie shared a heightened level of effort and shift in strategies when solving physics problems on assessments compared to practice problems. Aaron noted that on an assessment "she gives us equation sheets and they usually only have the equations that we're using on them." Since the equation sheet provided for participants had equations that could be used for all of the problems, covering multiple concepts, he had to use other strategies, such as "use process of elimination and try and figure out like the quickest way to get to where the answer here," to decide which equation to use.

When both Aaron and Judy reached a problem they could not answer, they noted how they would decide to move forward if this was an assessment situation. Aaron noted on problem one that "if I had this on the test, I'm skipping this problem. I'm going right to the next one, um, because this is like, me, not studying for like a week. And this is a really big test." Later when he had tried a problem multiple times, he decided to move on, "So we'll just say, for the sake of just getting an answer, which is what I would do on tests, all the time." Aaron and Judy both noted problem solving strategies in terms of earning or losing points on a problem. Aaron could not remember the units of a quantity and weighed his options, "Um, nineteen point six, we'll just leave it blank and miss a point, if this was a test." Judy implied that she would get some credit for her work, "So, I think I would probably leave this if I was, if I were doing a test, because at least I showed some effort. So here's my attempt at consoling myself and I would submit this, as it is right now." Both Judy and Aaron showed frustration with themselves in not being able to solve all of the problems. At one point, Aaron had to remind himself that he was not being assessed on his work, "Calm down, this isn't a test, you said that. I don't know, I don't know. I just need to calm down and do some physics." It is evident that the participants view and approach physics problems with different cognitive and metacognitive strategies based on their purpose: practice or assessment.

Common Sense and Logic

During both the problem solving process and the follow-up questions, four of the seven participants mentioned common sense or logic as part of their thought processes for a total of 13 excerpts. When mentioning common sense or logic, participants were either doing so to answer a question without the use of mathematics, or they were using it to monitor their comprehension or check their answer.

Lana, Ellie, and Judy all used logic, or common sense, as a means to answer the physics problem. When asked which ball would hit the ground first in the first physics problem, Ellie first used common sense to answer the question:

> So initially, just common sense wise, I'm thinking that Cooper's ball is gonna hit the ground first, because they're both standing in the same location but Cooper's just dropping it straight down whereas Zoe is throwing it up initially. So common sense wise I know that my answer should be Cooper.

Ellie used the calculations from the second part of question one as a way to mathematically check her "common sense" answer. Although Ellie frequently used mathematics to solve the three physics problems, she reflected that she views physics problem solving as a very logical process. She reflected:

> I guess everybody's logical in solving physics problems, but I feel like I tackle it in a logical way. And then I also try to think, so like, I try to make sure I'm not getting too caught up in, like, the physics of it that I'm forgetting, like, the way the real-world works. And, like, does it actually make sense,

explaining how she uses logic to help her understand both the physics concepts and physics problems.

Lana and Judy also used logic or common sense to answer the physics problems, but they used it as a secondary approach to solving the problem after they failed to do so using mathematics. Judy's response to the question of which ball will hit the ground first was very similar to Ellie's, "Logically I would think that Cooper's ball would hit the ground first, because Zoe's would have to travel upwards and then downward" but since she could not support it with mathematics as Ellie did, she did not seem as confident in her answer. Both Lana and Judy were unable to mathematically solve any of three physics problem, but still attempted to answer each problem. At one point in both interviews, Lana and Judy noted how they felt their logic or common sense approach was not as valued as a mathematical answer. Lana noted about one of her answers, "I feel like it wasn't real physics. It was just my brain talking about the logic behind things" and similarly Judy explained “I can probably just put down a general answer based on logical reasoning instead of actually putting it down.”

Participants also used common sense or logic as a way to monitor their comprehension or check a final answer. Both Catherine and Judy shared in their follow up question that using “logic, like, does this make sense” (Catherine) is a way to monitor their comprehension. Judy elaborated that in addition to common sense and logic, she tries to picture how the situation would play out in real life:

> I was thinking about, like, if I were the person doing this kind of so, like with Cooper and Zoe’s problem. Like, if I were there with my brother, and we dropped a ball and throw it up, like, what would actually happen? Like, how would I imagine that playing out? Um, and just like, I guess I just got that from my general knowledge of the world, I feel like, I knew that the ball, like Cooper's ball would hit the ground first because not because of the actual physics behind it, but because of my general knowledge of the world, and I knew that that ball is gonna hit the ground first. I just had to figure out how I knew that.

Ellie sees common sense or logic as a way to check her work:

> I know I don't really check my work. Like, if it was a test, I would, um (pause) I don't know, I never really run the numbers again, but I would just look over it and make sure it makes sense again before I moved on to the next problem. But otherwise, if it's not like an exam, I’m not really a work checker.

Ellie inferred that checking her work meant recalculating or attempting the problem another way, which was not something that she, nor any other participant, did.

Although Ellie claimed in the follow-up question that she is “not really a work checker,” she demonstrated directly using common sense and logic as a way to check her understanding or mathematical work on multiple occasions. When transitioning from part B to part C on physics problem two, Ellie checked her comprehension of the problem and physics concepts using logic:

> Um, now this time, because I know that there is, um, acceleration and I know that like, logically, it's gonna accelerate with the two kilogram um mass falling down and that’s pulling the five kilogram mass right. Well, like, logically, speaking, I know that the gravity is gonna make the two kilogram mass fall down.

And later, she used logic to check the answer of that same question:

> So, then I'm thinking, does that logically make sense two point eight meters per second squared. I think, yeah, that it makes enough sense, I guess. So, that's my final answer for part B, two point eight meters per second square.

Ellie was able to use logic to monitor her comprehension of the physics problems and check that her answer made sense. Thinking of physics problems as a logic problem or common sense seemed to help many participants solve the problems both cognitively and metacognitively.

Summary

Participants demonstrated using cognition and metacognition in a variety of ways during the think aloud interviews. Planning and reading were the most used problem solving processes during the think aloud interview. Information management and comprehension monitoring were metacognitive processes that were most frequently observed being used while the participants were solving the three physics problems. If a participant used a problem solving process in combination with a metacognitive process, it happened more frequently during the problem solving planning process. This means that much of the cognitive and metacognitive processes used by the participants during the think aloud interview happened at the beginning of their problem solving process, while they were planning and setting up their work for their problem rather than at the end of the problem when they were calculating and answering the question. In addition to using problem solving and metacognitive processes to solve three physics problems, participants noted that they were influenced by three other things: (a) teacher influence and expectations, (b) problems as assessments, and (c) common sense and logic. These three emergent themes were ideas participants shared as a reason for choosing their approach to solving the problems, shaping their cognition and metacognition.

In What Ways do Current High School Physics Students Voice Dissatisfaction with Their Content Knowledge While Solving a Physics Problem, and Does that Dissatisfaction Lead to Conceptual Change?

All participants shared at least one instance of dissatisfaction with their understanding of either the information given or their understanding of the physics concepts as shown in Table 15. Participants shared two different types of dissatisfaction, internal and external. Each participant used their dissatisfaction differently. Some students used their dissatisfaction to look for a different approach to solving the problem while other students acknowledged their dissatisfaction and moved on. Additionally, the only times participants engaged in debugging by asking for help or clarification was when they were expressing external dissatisfaction, dissatisfaction with the information given in the problem. There were no instances where participants who expressed dissatisfaction with their own understanding asked for help or clarification.

Internal vs. External Dissatisfaction

In the think aloud interviews, participants shared two different types of dissatisfaction. When a participant shared internal dissatisfaction, they were sharing dissatisfaction with their own understanding of the physics content. Participants expressed external dissatisfaction when they were not sure of the information given to them in the problem. Overall, participants were more likely to share internal dissatisfaction with 76% of the 51 dissatisfaction statements expressing internal dissatisfaction. Not all participants communicated both types of dissatisfaction. One participant shared only internal dissatisfaction (Ellie), three shared only external dissatisfaction (Samir, Catherine, Jessica), and three shared a combination of the two (Lana, Judy, Aaron).

After sharing their dissatisfaction, some participants (Lana, Samir, and Aaron) did debug by asking for help or clarification, but these three participants only did so when they were expressing external dissatisfaction. Participants who expressed internal dissatisfaction did not debug by asking for help. Other participants did express their dissatisfaction as questions (Catherine – internal, Aaron – internal and external), but the questions were directed towards themselves and not the interviewer. Further discussion of what actions participants took following their statement of dissatisfaction is in the sections to follow.

Three participants shared markedly more statements of dissatisfaction (Lana - 11, Judy - 11, and Aaron - 19) than the other participants. The next highest number of dissatisfaction statements expressed by a participant (Samir, Catherine, and Ellie) was 3. Most of the statements made by these three participants were expressing internal dissatisfaction as shown in Table 15. Notably, the three participants with the largest number of dissatisfaction statements each only answered one problem correctly (Table 17). All other participants answered at least two questions correctly. The participants who shared the most overall dissatisfaction also provided the least number of correct answers.

Action Prior to Dissatisfaction

Table 35 shows a breakdown of what problem solving process the participants were engaged in prior to and immediately following their statement of dissatisfaction. Prior to making a statement expressing dissatisfaction with their understanding, the participants were engaged in all parts of the physics problem solving process (reading, planning, calculating, answering, and checking) as shown in Table 35. By far, more participants were in the planning and reading processes when they expressed dissatisfaction than any other process. Planning accounted for 41% of the occurrences and reading 26%. The problem solving process that led to the smallest amount of dissatisfaction statements was the checking process with only one statement. In addition, one participant was finished with the problem solving process and was in transition between problems when they shared their dissatisfaction. This suggests that dissatisfaction is most likely to occur early in the problem solving process.

Table 35

Summary of What Participants Were Doing Prior to and Immediately After Their Statement of Dissatisfaction

Physics Problem Solving Process Prior to Statement of Dissatisfaction		#	Physics Problem Solving Process After Statement of Dissatisfaction		#
Reading		13	Reading		6
Planning		21	Planning		24
	- draw a picture or diagram	1		- draw a picture or diagram	0
	- arranging information	1		- arranging information	1
	- list knowns and unknowns	4		- list knowns and unknowns	3
	- choose a concept or equation	15		- choose a concept or equation	20
Calculating		7	Calculating		3
Answering		8	Answering		8
Checking		1	Checking		1
Moving On		1	Moving On		9

Within the planning phase, 15 of the 21 dissatisfaction statements were made while students were choosing a concept or equation. Two thirds of the statements were shared while participants were reviewing the given equation sheet or recalling an equation from memory. For example, Ellie was trying to recall the equation she needed to rework problem 3 when she said “Um. So now I'm gonna try to think. What, what (inaudible) okay. I’m trying to remember the equation used for, going back to the equation sheet.” The other five statements in this category were made while conceptually reasoning through a problem “which is very conceptual and I'm confused by it already” (Lana).

Action Following Dissatisfaction

Just as most participants were in the planning process prior to their statement of dissatisfaction, 47% of the time (20 of 51), participants engaged in the planning process after making their statement (Table 35). In 13 of 20 instances where participants followed up their dissatisfaction by choosing a concept or equation, they did so in a computational manner involving equations.

The second most frequent action participants did after expressing their dissatisfaction was deciding to move on to the next problem. On some occasions, it meant the participant made the decision to move on without an answer. For example, Judy decided “I can't figure out what the quantitative and I, I don't really have any other options to solve it, for now I would just probably (short pause) leave it blank and then come back to it.” For other participants, it meant moving on to the next question knowing that their answer was not correct:

> But then I'm just mul-, dividing and I'm just gonna get six. So that doesn't make sense. (sigh) So, then velocity final, when it’s, must be, no. (pause) So, ooo talking her out here, I feel like I'm just confusing myself and that I should just get an answer (Aaron).

Likewise, when the participant decided to answer the question following their dissatisfaction, many did so knowing that they would not get the correct answer like when Lana shared “Um, and my thought process behind that I'm not entirely sure honestly.”

Jessica had a unique response to her dissatisfaction. In her think aloud interview, Jessica only shared one statement of dissatisfaction that was aimed at the lack of information given in problem 1C: “I feel like, I don't have enough information for this one, just because it doesn't tell me how long it's going up with a speed of five meters per second before it starts going back down again.” Following the statement, Jessica moved on to the next problem and did not come back to problem 1C during the think aloud interview. With just this context, Jessica’s statement does not seem to share dissatisfaction with her understanding of the physics concepts. After the think aloud interview, Jessica sat back down with problem 1C and correctly solved the problem. When she emailed the photos of her work from the think aloud interview, she included her new work for problem 1 as well as a written narrative of her reasoning (see Figure 18). I do not know what prompted Jessica to go back to problem 1C, nor do I know if Jessica accessed any resources to help her with the problem. Her decision to go back and revisit the problem is evidence that Jessica was more dissatisfied with her own understanding of problem 1C than she shared in her statement.

Dissatisfaction Sparking Change

Conceptual change is a process that takes time, so it was not expected that a participant would experience conceptual change while working on the problems. While there is no evidence of participants undergoing conceptual change, there is evidence of the participant’s dissatisfaction sparking a change in how they thought about or approached the problem. Both Judy and Aaron use their dissatisfaction to rethink how they were approaching the problem. After Judy stated, “I'm right now confused about what I'm supposed to do," she decided to use logic to approach the problem instead of computationally solving the problem. Aaron, on at least two occasions, used his dissatisfaction as a resetting moment. When working on problem one, Aaron's dissatisfaction statement, "Wait, we're looking for, hold on...Okay. Yeah. So stop. What are you doing?" prompted him to reestablish the purpose of the problem and allowed him to reset this thinking. Again in problem 2, Aaron caught himself going down a wrong problem solving path "Nope. That's not right. That doesn't seem correct though ok," and he reset himself, going back to his original attempt at the problem. With both of these participants, their statement of dissatisfaction allowed them to shift how they were approaching the problem.

Lana, Ellie, and Jessica went a step further than just resetting their approach, all three of them completely redid the problem as a result of their dissatisfaction. As Lana was reading problem 2C, she exclaimed, "I see what I did here," and went back to re-answer problem 2B. Ellie was sharing her reasoning for problem 3 when she caught herself using the words speed and velocity interchangeable:

> My reasoning that it's zero for all of these tracks is, it's said, in the description that the radii of the tracks and the speeds of the cars are, are no, it said traveling around a circular track at a constant speed. Oh wait. Okay. Okay. Now I've changed. I changed my mind because, um (pause) it's a constant speed, which is true. However, the velocity is not constant because travelling in a circle, so it's constantly changing direction. So the velocity is not constant. So, um, I know the net force can't be zero.

As a result of this dissatisfaction, Ellie chose a different approach to problem 3 and started over. Jessica made a similar decision to redo problem 1, but since this occurred after the think aloud interview, it is unknown directly how her dissatisfaction led to the decision to redo the problem.

Summary

For students to engage in conceptual change, they must first be dissatisfied with their current understanding before they decide to start the process of shifting their conception (Dole & Sinatra, 1998; Posner et al., 1982). On 51 occasions during the seven think aloud interviews, the participants expressed dissatisfaction with their understanding. The dissatisfaction shared was either for their understanding of the concept or their understanding of the information shared in the problem. In most cases, participants were engaged in the planning phase of the problem solving process prior to and after the statements of dissatisfaction, specifically choosing a concept or equation for the problem. Some participants used their dissatisfaction to spark a change in their thinking about the problem or choose a different way to solve the problem. Other participants did not change their strategy for solving the problem and continued the problem or moved on knowing that their answer would be wrong, if they were able to give an answer.

Chapter Five

As high school students walk into their first physics class, they have already formed conceptions of physics concepts based on prior experiences, knowledge, and beliefs. These prior conceptions do not always align with the scientifically accepted physics concepts that are being taught (Disessa, 1996; Gunstone et al., 1992; von Aufschnaiter & Rogge, 2010; Vosniadou, 1994). Typically, in a high school physics classroom, problem solving is a key resource and tool used to help students learn the physics content and align their prior conceptions with the scientifically accepted concept (Kim & Pak, 2002; Mulhall & Gunstone, 2012).

Conceptual change theory explains that the student must first be dissatisfied with their current conception in order for them to then start the process of shifting their prior conception towards the scientifically accepted conception (Dole & Sinatra, 1998; Posner et al., 1982). If a student is going to find dissatisfaction with their current conception, they will engage their understanding metacognitively (Flavell, 1979). Prior research has shown that it is not enough to know if a student has used metacognition; but it is also important to understand how, when, and why the student engaged with their metacognitive knowledge (Kung & Linder, 2007; Moser et al., 2017; Osman, 2010). To elaborate on this line of research and better understand how and when during the problem solving process students use metacognitive knowledge while solving physics problems, this study was guided by the following research questions:

1. How do current high school physics students use cognition and metacognition to solve physics problems?
2. In what ways do current high school physics students voice dissatisfaction with their content knowledge while solving a physics problem, and does that dissatisfaction lead to conceptual change?

A mixed methods study was designed to answer the two research questions. Seven high school physics students responded to the Physics Metacognitive Inventory (Appendix D; Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013) and participated in a think aloud interview (Ericsson & Simon, 1993; van Someren et al., 1994) while solving three physics problems (Appendix E). The think aloud interviews were coded for participants' use of cognition as defined as physics problem solving processes, metacognitive processes (Table 5; Appendix G), and statements of dissatisfaction (Appendix I). Additional, three emergent themes, (a) teacher influence and expectations, (b) problems as assessments, and (c) common sense and logic, were noted in the interviews (Table 6; Appendix H). Descriptive statistics were provided for the PMI as well as the quantification of the think aloud interview codes. A case was written for each participant that shared their cognition, metacognition, dissatisfaction, and problem solving style. Included in each case is a similarity matrix heatmap of the participant's problem solving and metacognitive co-occurrences. Summaries were made across cases and were organized by research question.

How do Current High School Physics Students Use Cognition and Metacognition to Solve Physics Problems?

Cognition (problem solving) was categorized into the five problem solving steps in which the participant was engaged (Etkina et al., 2014; Knight, 2013; Phang, 2009, 2010). Metacognition was conceptualized using the eight subprocesses of metacognition (Schraw, 1998; Schraw & Dennison, 1994; Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013). The way the participants moved through problems was categorized by what type of physics knowledge they used and their rhythm for solving problems. While each participant had a unique way of incorporating cognition and metacognition into their problem solving approach, there were commonalities across the seven participants. Participants used the problem solving processes of planning and reading the most while solving the three physics problems in the think aloud interview. Overall, in the problem solving process, they used information management and comprehension monitoring the most of all of the eight metacognitive processes. When participants were engaged in using both a problem solving strategy and a metacognition process, they were most likely to do so in the planning phase of problem solving.

Participants were categorized by how they moved through the problems (arrow or iterator) and how they applied different types of physics knowledge (conceptual, computational, hybrid). Three emergent themes came from the coding of the think aloud interviews. In addition to problem solving and metacognitive processes, participants shared three influences on their problem solving process: (a) teacher influence and expectations, (b) problems as assessments, and (c) common sense and logic. These three emergent themes were ideas that participants shared as a reason for choosing their approach to solving the problems, shaping their cognition and metacognition.

Cognition

In the original proposal for this study, cognition was going to be measured using the Force Concept Inventory (Hestenes et al., 1992). Due to limitations caused by the COVID-19 pandemic and the need to do the think aloud interviews virtually, the FCI was not used since I could not guarantee the security of the measure. For the purpose of this study, student cognition was measured as the use of problem solving strategies since it was observable in the think aloud interviews.

The problem solving process that the seven participants engaged in the most while solving the three physics problems was planning. Further, participant engagement in cognition was front loaded in the problem solving process with reading and problem solving combining to account for two thirds of the instances coded as a problem solving process. Participants did the majority of their cognitive work in the early parts of the problem solving process. This aligns with Phang's (2009) findings that planning had the most overall codes of all of the problem solving steps and that over half of the student problem solving work occurs before they start calculating the problem.

Checking was the problem solving process that participants used the least. One participant, Ellie, noted that she only checked her answers when she was working through an assessment. Phang (2009) reported different results from her study with checking being the third most highly used problem solving step, after planning and calculating. The discrepancy in these findings may be because of how the two studies defined checking. Phang (2009) defined checking as the process of evaluating, justifying, and/or monitoring. I defined checking as the "participant is making sure that their work or answer makes sense/is correct" (Appendix G). A participant checking their work at the completion of the problem is an evaluation process as opposed to monitoring their work during the process, which would be comprehension monitoring. Using Phang's expanded definition of checking, there would have been more instances of participants checking their work, but the definition of checking used for this study was more aligned with the definitions of checking taught as part of the problem solving process in physics textbooks (Etkina et al., 2014; Knight, 2013).

Metacognition

Physics Metacogntive Inventory. Research has used the PMI in a variety of ways such as translating the instrument into additional languages (Haeruddin et al., 2020; Ünlü & Dökme, 2019), creating and testing a heat and temperature specific metacognitive inventory (Hikmah et al., 2021; Sukarelawan et al., 2021), creating coding categories based on the PMI (Mota et al., 2019), and analyzing relationships between metacognition and other constructs (González et al., 2017; Kustanto & Utari, 2018; Marzoli et al., 2021). Research has not been located that investigated how students scored the individual metacognitive processes, which makes it hard to compare the results of this study to those of previous studies. Overall, the seven participants indicated on the PMI that it was "usually true" that they engaged in the 26 metacognitive strategies while working on physics problems. The item that the participants noted that they were most likely to engage in was debugging by seeking help. Further discussion on how the participants engaged with debugging will be shared with the think aloud results, where the majority of the data on debugging emerged.

The five strategies that the participants indicated on the PMI that they used the most while solving physics problems fell into different metacognitive processes. There was no clear pattern of a most used process when looking across the individual items. This could indicate a balanced approach to using metacognitive strategies while solving physics problems. It could also mean that student use of metacognitive strategies is strategy specific rather than process specific. For example, a student may feel that they frequently used one specific comprehension monitoring strategy, but not the others resulting in a high score for that item, but not for the process as a whole.

The five strategies that the participants indicated on the PMI that they used the least while solving physics problems were evaluation and comprehension monitoring metacognitive processes. Further discussion of the participant's use of evaluation and comprehension monitoring will follow with the addition of the think aloud data.

Think Aloud. In the think aloud interviews, the participants were observed engaging in more regulation of cognition processes than knowledge of cognition processes. This means the participants were more likely to engage in metacognition as a way to monitor and control their work than they were to engage in a way that they were sharing their knowledge of how to solve the problems. These results are different from Mota et al. (2019), their participants sharing more knowledge of cognition statements than regulation of cognition when reflecting on their understanding. This difference may be due to the fact that the participants in their study were reflecting after solving the physics problems and comparing their answers with peers while the participants in this study shared their metacognitive statements in real-time while solving the problems (Mota et al., 2019). Since there was not a large difference in the way that participants responded to knowledge of cognition and regulation of cognition processes on the PMI, it is possible that this difference this could be a limitation of the think aloud interview. The data provided by a think aloud interview is limited by what the participant is willing to, or comfortable with, sharing (Ericsson & Simon, 1993; van Someren et al., 1994). It is possible that participants did not want to share why (or why not) they knew how to solve the problem, or it is also possible that the knowledge of cognition process was not one that the participants noted as a separate thought process to share out loud.

The metacognitive processes that the participants were observed using the most were comprehension monitoring and information management. This means that the participants were most likely to assess their progress and comprehension as well as to use strategies to make them more successful. Similarly, Phang (2009) found that physics students tend to monitor their work throughout multiple steps in the problems solving process. Osman (2010) noted that the use of metacognitive strategies raises the students' awareness of their thought processes, and Veenman and Spaans (2005) found that metacognitive skills are interdependent. It may be that student use of other physics specific metacognitive strategies, such as drawing a diagram or identifying the important parts of the problem, may increase the use of these two monitoring strategies.

The metacognitive processes that the participants were observed using the least were evaluation and procedural knowledge. Participants did not frequently check their work at the completion of the problem nor share their thoughts on how to do the problems. In Mota et al.'s (2019) study, evaluation and procedural knowledge were metacognitive processes that were in the middle of the frequency spectrum. As shared earlier, differences in how and when students were sharing their metacognitive refection may account for the different findings in this study and that of Mota et al. (2019). Students may be more likely to reflect on how they solved the problem and their final answer while reflecting after they have completed and checked the problem with peers as compared to when they are in the process of solving the problem.

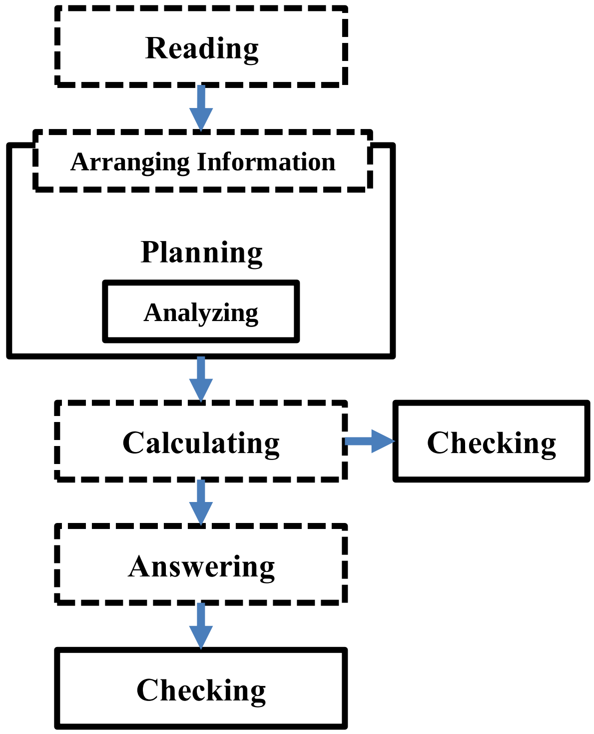
For the most part, observations from the think aloud interview aligned with participant responses from the PMI. There were two exceptions: comprehension monitoring and debugging. Comprehension monitoring was the metacognitive process that the participants rated as using the least frequently on the PMI, but was one of the processes that participants were observed using most frequently. It is possible that since comprehension monitoring is usually intertwined with another problem solving step, such as planning or calculating, the participants did not view it as a separate step in the problem solving process like they do checking/evaluating. The problem solving process that is typically taught in physics textbooks and classrooms (Etkina et al., 2014; Knight, 2013) explicitly lists checking the final answer (evaluation) as a step, but does not list checking their progress while working on the problem (comprehension monitoring).

The findings for debugging were the opposite of those of comprehension monitoring where the participants indicated that they used debugging frequently on the PMI but were observed using debugging less frequently in the think aloud interviews. It is possible that this disconnect was a result of the context of the think aloud interview and that the participants would have engaged in debugging more frequently if they were in their natural environment for learning physics. Lana mentioned that she would normally use her notes (which were not available to her with this study) when she did not understand something, and Aaron shared that he would have asked his teacher for clarification on one of the problems. While some students did ask the interviewer questions while working on the problems, perhaps if students been in a classroom setting with their peers and teacher, they would have been more comfortable debugging and asking for help. Rahayu et al.'s (2018) findings would support this assumption in that their participants debugged by looking information up on their phones, referencing a sample problem, and asking questions. The first two resources, especially, were not available to the participants in this study. If the participants had more resources available, they may have debugged more frequently.

Cognition and Metacognition Co-Occurrences. A similarity matrix heat map displaying the co-occurrence of statements coded as physics problem solving and metacognitive processes during the think aloud was created for each participant (Tables 19, 21, 23, 25, 27, 29, and 31) as well as for the overall counts for all seven participants (Table 34). Individual patterns of problem solving and metacognitive process co-occurrences varied greatly between participants. This ranged from Lana and Judy both having all but one co-occurrence in the planning stage of problem solving to Aaron having at least one co-occurrence within each column (problem solving) and row (metacognition) within the matrix. Even with the variety across the similarity matrix heat maps for the seven participants, there were clear trends that emerged.

Overall, the seven participants were observed using problem solving strategies and metacognitive processes together more during the planning phase than any other phase of problem solving. Further, the intersection of planning and information management on the heat map had the largest amount of co-occurrence counts. This aligns with Phang's (2009) finding that planning and analyzing (during the planning phase) were the problem solving processes with two of the three largest instances of metacognitive codes associated with them. The planning phase of problem solving is ripe for metacognition use and a potential location to help embed and cultivate more metacognitive use in physics problem solving.

Model of Metacognition in Physics Problem Solving. As a whole, Phang's (2009, 2010) model (Figure 20) aligns with the way that the seven participants used cognition and metacognition while working on the three physics problems. There are three areas of the model, reading, arranging information, and checking, that I would propose adjusting or expanding based on the work of the seven participants in the study.



Note: Solid boxes indicate metacognitive processes while dashed boxes represent cognitive processes.

Figure 20.

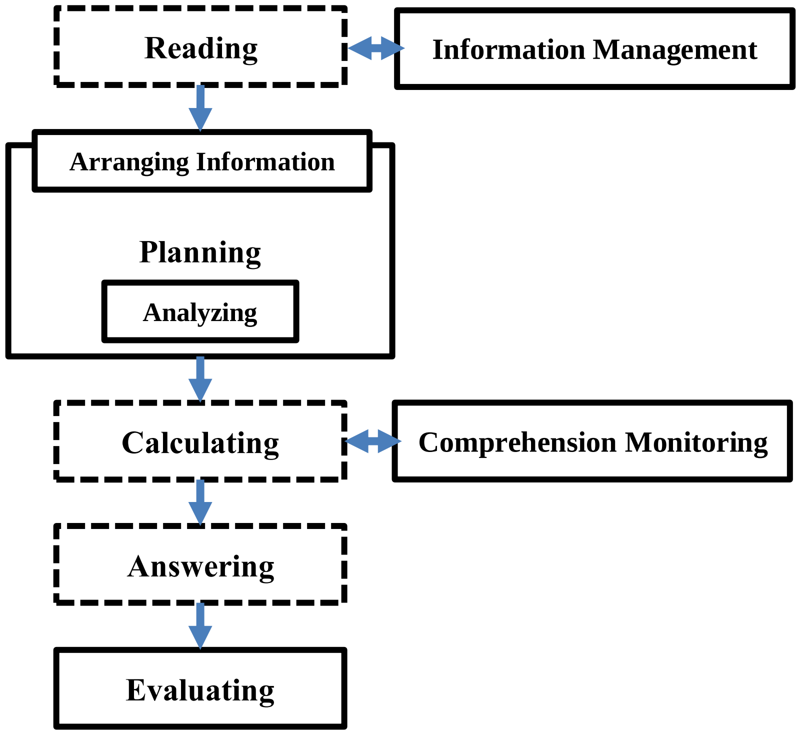
Phang's (2009, 2010) original pattern of physics problem solving

While participants were reading the problem, they frequently engaged in a metacognitive process. Phang noted this in her 2009 dissertation, explaining that students used different strategies to monitor and reflect on their understanding while reading the problem, but did not include it in her 2010 model. Based on the work of the seven participants, I would extend Phang's model to add information management as a possible metacognitive process that happens as a result of reading, but before the student engages in the planning phase of problems solving. Further, I would use a double sided arrow to show that students frequently go back and forth between reading the problem and managing the information given to them.

For all of the participants, the problem solving process in which they were most likely to engage in a metacognitive process was the planning phase. This aligns with Phang's (2009, 2010) model for physics problem solving shown in Figure 20. Phang's model noted that the planning phase, particularly the analyzing aspect of it, involved the use of metacognition. In Phang's 2009 model, arranging information is included as a metacognitive process, but in the 2010 model, the shading indicates that it is a cognitive process. Data from this study aligns with Phang's original model that arranging information is a metacognitive process. When students were arranging information, they were frequently doing so by drawing and labeling a picture or diagram or highlighting important information from the problem, which aligns with Taasoobshirazi and Farley's (2013) definition of information management. I would indicate in the model that arranging information is a metacognitive process.

Phang's model (2009, 2010) included two steps, while calculating and after answering, when students in her study typically checked their work, if they chose to engage in the checking process. While the data from the seven participants from this study showed agreement that they tended to check their work while calculating and after answering the problem, I would argue that checking work during those two problem solving processes served two distinct metacognitive purposes. Evidence from the think aloud interviews indicates that during the calculating step of problem solving, students were likely to monitor their comprehension, not check or evaluate their work. Further, Ellie explained in the follow up question that checking her work referred to numerically evaluating the answer at the end of the problem, usually by recalculating the answer. She shared that she did not feel she checked her work very often despite evidence of frequently monitoring her comprehension while working on the problems. After answering the problem, the participants checked their work as a way of evaluating their answer. To show the different metacognitive processes used in these two checking opportunities, I would rename them: checking during calculating would now be labeled comprehension monitoring and the checking after answering would be evaluation. Phang noted a similar difference in the ways students checked their work, but still called them both checking in her model. By renaming the checking steps as comprehension monitoring and evaluating, the model more clearly explains how the students are using metacognition and used terminology more likely associated with the definitions of metacognitive processes (Schraw, 1998; Schraw & Dennison, 1994; Taasoobshirazi & Farley, 2013) rather than problem solving (cognitive) processes. Additionally, I would use a double sided arrow between calculating and comprehension monitoring to show how students go back and forth between the two while solving a physics problem. checking during the calculating process.

Figure 21 shows the suggested changes to Phang's (2009, 2010) model of patterns for physics problem solving. Information management was added to reading with a double sided arrow to show the tango the participants did dancing between reading the problem and organizing the information given to them in the problem. The arranging information box was made solid to indicate that it is a metacognitive process rather than a cognitive process. And finally, the box labeled checking connected to calculating was renamed comprehension monitoring and the box labeled checking connected to answering was renamed evaluation. This was done to distinguish between the two different metacognitive processes the participants were engaged in at that time. These changes provide a more detailed model of how high school physics students use cognition and metacognition while solving physics problems.



Note: Solid boxes indicate metacognitive processes while dashed boxes represent cognitive processes.

Figure 21.

Metacognition use in physics problem solving adapted from Phang's (2009, 2010) pattern of physics problem solving

Problem Solving Style

Each of the seven participants had a different approach to how they engaged with the three physics problems. Participants in this study were categorized based on how they tackled the physics problems in terms of how they moved through the problems and how they engaged their conceptual and computational physics knowledge. In terms of how they moved through the problems, participants were categorized as arrows when they moved straight through the problems one at a time and as iterators when they continued to rethink and revisit problems. Kohl and Finkelstein (2008) found similar patterns of problem solving styles when investigating how physics students use multiple representations while solving physics problems. The researchers tracked how, for how long, and in what order students used different representations while solving physics problems. Kohl and Finkelstein noted a range of complexity of paths used to solve problems including a participant who used three representations, engaging with each representation only once and a different participant who used a total of nine different representations with 23 transitions between those representations (2008). These descriptions align with the arrow and iterator classifications respectively. Further, Kohl and Finkelstein (2008) noted that novice problem solvers tend to have more iterative transitions between representations and look at those representations for shorter periods of time before moving to the next one as compared to expert problems. This could mean that the arrow problems solvers were more expert problem solvers than the iterators. These findings create a gap for further research to investigate how problem solving style correlates with level of physics expertise.

When looking at how students engaged with their physics knowledge, participants categorized as conceptual problem solvers relied mostly on conceptual understanding to answer questions, computational problem solvers used mainly equations to solve problems, and hybrid problem solvers used a combination of conceptual and computational knowledge. Phang (2009) also found that the participants in her study fell into three categories based on how they engaged with the different types of physics knowledge. Phang noted that there were students who avoided using equations, students who always used equations, and students who used equations when necessary. Likewise, Lucas and Lewis (2019) noted that many students try to find an equation to solve the problem rather than engage with the physics concepts. These three descriptions align with the categorization of problem solvers proposed in this study: conceptual, computational, and hybrid respectively.

Of the different combinations of problem solving styles displayed by the seven participants in this study, the hybrid problem solvers were more likely to answer the problems correctly. The hybrid problem solvers were able to switch between computational and conceptual knowledge based on the type of problem. In some cases, the hybrid problem solvers would use conceptual knowledge to help them set up their problem and then use the computational knowledge to solve for the unknown. This aligns with Kuo et al.'s (2013) finding that students who are more successful with understanding physics concepts are more likely to pick the correct tools to solve the problem. This could be related to the level of physics knowldege, from novice or expert, of the problem solver. Larkin (1979) found that when working on a physics problem, experts tend to do qualitative analysis before using equations to solve the problem while novices start by looking for terms in the equation that match the problem.

Additionally, Kohl and Finkelstein's (2008) made a distinction between novices and experts in that experts engage in more analysis while novices tend to solve problems more algorithmically. This is compounded with Nandagopal and Ericsson's (2012) observation that students may not fully understand the underlying physics concepts even if they can computationally answer the problem correctly. These two ways of describing expert and novice work would indicate that experts use more of a hybrid approach to solving physics problems while novices use more of a computational approach. While I do not think that any of the seven participants were physics experts after one high school level physics class, I do believe that the students who were categorized as hybrid problems solvers were more competent than the computational and the conceptual problem solvers.

Teacher Influence and Expectations

The participants in this study frequently mentioned their teacher as part of their cognition and metacognition while solving the three physics problems. In these statements, the participants talked about both strategies their teacher taught them and expectations their teacher had of them. In some of these statements, the participant talked about the teacher influence in a positive light, helping them solve the problem, while other statements shared how the participant did not like or understand the strategy provided by their teacher. Nadelson et al. (2018) noted that teachers are part of the social, cultural, and community factors that influence a student's motivation to engage, or not engage, in conceptual change. The expectations that a teacher sets in the classroom concerning problem solving influence how and when students use their own prior knowledge and skills compared to strategies provided by their teacher. Teachers can integrate activities and supports to help their students critically evaluate their ideas (Nadelson et al., 2018). If students do not engage with their prior knowledge, they cannot engage in conceptual change. Further, Wade-James et al. (2018) found that students frequently use strategies because they are expected to, not as a way to further their understanding. Physics teachers could look for a way of balancing teaching problem solving and metacognitive strategies and supporting students to use them. This allows space for students to assimilate their old knowledge and strategies with the new strategies provided by the teacher (Hewson, 1992; Posner et al., 1982; Vosniadou, 1994).

Problems as Assessment

Many participants noted how they would address an issue with a problem differently if that problem were on a test. This indicated that physics students use different problem solving (cognitive) and metacognitive strategies with problems for practice versus problems which are an assessment. And in many instances, the participant noted they were showing work to get credit or that they would lose a point for forgetting to do a step in the problem. Phang (2009, 2010) shared a similar finding that students would mention different ways of gaining points while working on physics problems on a think aloud. This supports Lucas and Lewis's (2019) conclusion that on an assessment, students value finding an answer as more important than understanding and engaging with the underlying concepts in the problem.

When students are focused on how to earn points, they are more likely to have performance goals rather than mastery goals for the problem solving activity. This could be problematic because multiple researchers have concluded that students with a mastery goal orientation are more likely to engage in conceptual change than students with a performance goal orientation (Ranellucci et al., 2013; Taasoobshirazi et al., 2016;

Taasoobshirazi & Sinatra, 2011). Students who are focused on points, rather than understanding, may be less likely to engage in conceptual change.

The comments from participants about both their teacher's influence and the use of different strategies for assessments and practice problems validates Moser et al. (2017) and Wade-James et al.'s (2018) conclusions that some physics students may use a problem solving or metacognitive strategy because their teacher requires them to do so as part of the rubric for the assessment and not because the student finds it useful. When teachers ask students to show evidence of using specific problem solving strategies to get credit on an assessment, they may be collecting evidence that explains more of how the student uses the specified strategy rather than how the student understands the problem and underlying concepts.

Common Sense and Logic

The use of common sense and logic as part of the problem solving process was a frequent event, and further, four participants specifically noted the use as part of their cognition and metacognition. Participants used common sense or logic to answer questions conceptually, monitor their comprehension, and check their answers. Two of the participants shared that they did not feel that their common sense or logic answer was rigorous enough for a physics answer. I recommend a greater emphasis on understanding and validating physics students' prior experiences as physics knowledge. While many physics teachers agree that understanding a student's prior knowledge and skills is important to their instruction, only 45% of physics teachers report that it is an active part of their lessons (Banilower, 2019). Students come to physics with a wealth of experiences relevant to physics (Sherin, 2006) and tend to represent the physics problems in terms of what they already know (Pretz et al., 2003). This was true of most of the participants in the study. Jessica was an exception, as she relied on equations and computational knowledge to solve problems, similar to what some students did in Lucas and Lewis's (2019) study. It is important for teachers to understand their students' prior experiences relating to a concept so that they can tailor their teaching to better incorporate the students' knowledge that does align with the concept, and create experiences to help students reflect on their understandings. This allows students to build new knowledge from their existing knowledge more easily (Hewson, 1992).

Summary

In answering the first research question, how do current high school physics students use cognition and metacognition to solve physics problems, the majority of cognition and metacognition occurred during the planning stage of problem solving, which aligns with previous research (Phang 2009, 2010). With the large amount of cognition and metacognition during the planning stage, there are more opportunities for students to engage with their understanding, increasing the possibility of engagement in the conceptual change process.

Phang (2009, 2010) created a model of patterns of physics problem solving. Overall, data from this study aligned with Phang's model. The model included three areas: reading, arranging information, and checking, that where updated as a result of the think aloud data. First, it was noted that students use the metacognitive process information management while reading the problem, a cognitive process. Second, it was solidified that arranging information is a metacognitive process. And finally, the distinction was made between when a student engages in comprehension management during the calculating stage and when a student engages in evaluation after solving the problem. These changes create a stronger representation of patterns high school physics students use while solving physics problems.

In working on the problems, participants engaged with their physics knowledge in three ways, conceptually, computationally, or in a hybrid approach. Additionally, participants moved between problems in either an arrow or iterator fashion. The manner in which a participant moved through a problem could be an indication of level of expertise in physics (Kohl & Finkelstein, 2008; Larkin, 1979). Participants with a hybrid, iterator problem solving style answered more problems correctly, which could indicate a higher level of expertise in physics knowledge.

Additionally, three themes emerged as to outside influences on how the participants engaged their cognition and metacognition while solving problems: teacher influence, problems as assessments, and common sense or logic. Many of the cognitive and metacognitive strategies used by the students were taught by and frequently required by their teacher, aligning with Nadelson et al.'s (2018) placement of teachers as an influence on a student's motivation to engage in conceptual changed. Participants shared that they employ different strategies if they are taking an assessment or working on practice problems, mirroring findings of both Phang (2009, 2010) and Lucas and Lewis's (2019) that students focus on earning points rather than understanding when working on assessments. And finally, students often use common sense or logic as part of their cognition and metacognition, using old knowledge to support and build upon for their new knowledge (Hewson, 1992; Pretz et al., 2003; Sherin, 2006).

In What Ways do Current High School Physics Students Voice Dissatisfaction with Their Content Knowledge While Solving a Physics Problem, and Does that Dissatisfaction Lead to Conceptual Change?

A statement was categorized as dissatisfaction if the participant indicated that they were not happy with their understanding of a physics concept or the information given in the problem. Each statement of dissatisfaction was coded to note which problem solving step (Etkina et al., 2014; Knight, 2013; Phang, 2009, 2010) the participant was engaged in prior to and immediately following the statement. Participants shared statements of both internal and external dissatisfaction, and the majority of these statements occurred in the planning stage. Following their statement of dissatisfaction, participants were likely to engage with equations or move on to the next problem.

All participants in the study had at least one statement of dissatisfaction during their think aloud interview. While participants shared both internal and external dissatisfaction, there were more statements of internal dissatisfaction than external. Prior to sharing those statements of dissatisfaction and immediately following the statement, the participants were most frequently engaged in the planning phase of problem solving. None of the participants fully engaged in conceptual change during the think aloud interview as a result of their dissatisfaction, but many participants changed how they approached the problem following their dissatisfaction.

There was a wide range of number of dissatisfaction statements with one participant sharing only one statement of dissatisfaction during the think aloud interview and another participant sharing 19. The three participants who shared the largest number of dissatisfaction statements (19, 11, and 11) had the fewest questions answered correctly with only one correct answer each. The participants with fewer dissatisfaction statements (less than 3) did answer at least two questions correctly.

Internal vs. External Dissatisfaction

In the think aloud interviews, participants expressed both internal and external dissatisfaction. Internal dissatisfaction was expressed when the participant was not satisfied with their understanding of their physics knowledge or conceptual understanding. External dissatisfaction was shared when the participant was not satisfied with their understanding of the information given in the problems. As a whole, the participants shared more statements of internal dissatisfaction than external. Individually, participants used dissatisfaction differently with three participants only expressing external dissatisfaction, one participant only expressing internal dissatisfaction, and the other three sharing a mix of the two. Lebedev et al. (2021) found similar results when they had university physics students share their reflections on whether or not they changed their answers to a physics problem or not as a result of reviewing the solution. In their study, participants were more likely to share internal dissatisfaction in their reflections, statements categorized as “I do not fully understand” (p.10) than external dissatisfaction, statements categorized as “discontented.” (Lebedev et al., 2021, p. 10).

Both types of dissatisfaction are effective in assisting the learning process (Lebedev et al., 2021), and could lead to engagement in conceptual change.

Action Prior to Dissatisfaction

When the participants shared their statements of dissatisfaction, most occurred early in the problem solving process, specifically when they were reading the problem or engaging in the planning phase of problem solving. If participants were in the planning phase, they were most likely picking a concept or equation to solve the problem. Using metacognitive strategies often leads to the use of other metacognitive strategies (Veenman & Spaans, 2005) and can make students more aware of their own thought processes (Osman, 2010). Phang (2009, 2010) noted that the planning phase of problem solving is rich with metacognitive use. Further, many of the physics specific metacognitive strategies that were in the PMI, such as drawing a free-body diagram and identifying the important parts of the problem, (Taasoobshirazi et al., 2015; Taasoobshirazi & Farley, 2013) align well with the early stages of problem solving. It is possible that the use of the physics specific metacognitive strategies sparked the use of comprehension monitoring which led to the dissatisfaction.

Lebedev et al. (2020) found success in their “question-solution-reflection” framework, which had students reflect on their problem solving at the end of the problem after reviewing the correct solution to the problem. Based on the evidence from this study that the majority of metacognition happens in the early stages of problem solving, I would suggest having students reflect on their understanding during or just after the planning stage of problem solving rather than at the end of the problem. Evidence from the seven think aloud interviews in this study showed that the planning step of the physics problem solving process is rich with opportunities for students to engage in the comprehension monitoring metacognitive process. This reflection may increase the students' chances of finding dissatisfaction, which is the first step towards conceptual change.

Action Following Dissatisfaction

The two most frequent actions participants that engaged in following their statement of dissatisfaction were to choose an equation to computationally solve the problem or move on to the next problem. Very few of the participants engaged with the underlying concepts in the problem. This aligns with what Lucas and Lewis (2019) noted that students focus on finding an equation to solve the problem rather than trying to understand the physics concepts. They explained further that finding an answer to the problem is more important than understanding the underlying concept (Lucas & Lewis, 2019). In these cases, students can solve the problem correctly, but may not fully understand nor gain further understanding of the concepts involved in the problem (Fink & Mankey, 2010; Kim & Pak, 2002; Mulhall & Gunstone, 2012; Nandagopal & Ericsson, 2012), and research has shown that more practice solving problems is not the answer (Kim & Pak, 2002). In many of the interviews, I shared that I was interested in the participants thought processes and not whether they got the problems right or wrong to encourage students to share more of their understanding and not just their answers. Similar to Kim and Pak's (2002) participants, there seems to be a gap between some of the participants' conceptual knowledge and their use of equations.

When students chose to move on to the next problem, many times they acknowledged that they did not have the correct answer, or even any answer, as they did so. Numerous studies have noted that motivation to engage plays a significant role in conceptual change (Dole & Sinatra, 1998; Nadelson et al., 2018; Taasoobshirazi et al., 2016; Taasoobshirazi & Sinatra, 2011). The decision to move on may signal that the participant is not willing to engage with or is leaving the conceptual change process. This could also mean that the participant came to the realization that they did not have the tools to solve the problem.

Some participants did engage in debugging by asking for help following their statement of dissatisfaction. The participants who asked for help or clarification had all expressed external dissatisfaction. There were no participants who asked a question directed at the researcher (debugging) following a statement of internal dissatisfaction. As discussed earlier, I believe the participants would have used different debugging strategies, such as reviewing their notes or asking a peer or teacher, had they been in their normal physics classroom environment. I would question whether the trend that the only participants who asked for help were those who were expressing external dissatisfaction would hold true in a classroom environment.

Dissatisfaction Sparking Change

While none of the participants showed evidence of starting the conceptual change process as a result of their dissatisfaction, five participants did shift to a different problem solving strategy or used different physics concepts to solve the problems. Nadelson et al.'s (2018) model emphasized that conceptual change is a complicated, non-linear process that takes time, so it would not have been expected for a student to fully engage in conceptual change during the think aloud interview. In the cases of the five participants who did shift their strategy or thinking, they first monitored their comprehension, which lead to the dissatisfaction. They then acted in a manner to help address their dissatisfaction such as rereading the problem or looking at the equation sheet. Hewson (1992) noted that comprehension monitoring is an important part of the conceptual change process.

I would propose that an additional metacognitive process, debugging, is an integral part of the conceptual change process. Different models of conceptual change explain that for a student to engage in conceptual change, they must first be dissatisfied with their current conception (Dole & Sinatra, 1998; Posner et al., 1982) which is an act of comprehension monitoring. But research has shown that it is not enough for a student to be metacognitive and find dissatisfaction with their conception, they also need to take the next step in order to make sense of their misunderstanding or further their understanding (Kung & Linder, 2007; Moser et al., 2017). In this study, there were many instances where the participant was dissatisfied with their understanding but chose to move on rather than debug and further engage with their dissatisfaction.

This action of using strategies to fix errors and change learning such as asking for help or looking for other resources is how Taasoobshirazi and Farley (2013) defined debugging for their Physics Metacognitive Inventory. These are actions that were observed by the participants in the think aloud. For a student to start the process of conceptual change, they need to not only find dissatisfaction with their current conception by monitoring their comprehension, but also engage in the debugging process to seek out help in shifting their understanding. I would propose an additional step "Are you engaged in debugging to address your dissatisfaction?" in Posner et al.'s (1982) Conceptual Change Model as shown in Figure 22. By adding this step to the CCM, it shows the process that some participants in this study were observed doing where they were dissatisfied with their current conception but did not engage in seeking help. This meant that they did not get to the point in the process where they could engage with a new conception to see if it met the conditions of being intelligible, plausible, and extendible. This step demonstrates another point where students can leave the conceptual change process.

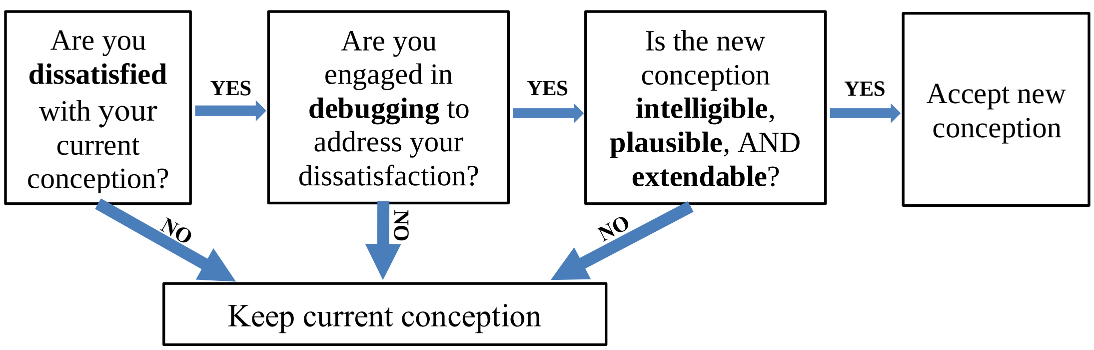


Figure 22.

Debugging as an additional step in Posner et al.'s (1982) Conceptual Change Model

Summary

In answering the second research question, in what ways do current high school physics students voice dissatisfaction with their content knowledge while solving a physics problem, and does that dissatisfaction lead to conceptual change, the seven participants were most likely to share dissatisfaction during the planning stage of problem solving. Participants shared statements that expressed both internal and external dissatisfaction, similar to participants in previous studies (Lebedev et al., 2021), but participants only debugged by asking for help when it was an external dissatisfaction statement. After sharing their statement of dissatisfaction, participants were most likely to return to the planning phase of problem solving by looking for an equation to solve the problem. Some participants chose to move on following their dissatisfaction, choosing not to engage with their current conceptions of the physics content. Both actions mirror Lucas and Lewis's (2019) findings that students are more likely to engage with equations than the underlying physics problems.

Dissatisfaction as a result of a student monitoring their comprehension is an important part of conceptual change as it is the spark that starts the process (Dole & Sinatra, 1998; Hewson, 1992; Posner et al., 1982). But as demonstrated in this study, dissatisfaction does not directly lead to engagement in the conceptual change process. The student must also engage in a second metacognitive process, debugging, to seek help or resources in an attempt fill the gap in understanding that was the source of the dissatisfaction. This would mean that a student should engage in two metacognitive processes, comprehension monitoring and debugging, to start the process of conceptual change. Additionally, by adding the additional step of debugging to the CCM, it explains another early exit point in the conceptual change process where the student chooses to move on rather seek out resources.

Implication

Based on the results of this study, the following recommendations are made for high school physics teachers: (a) focusing on the problem solving planning stage; (b) explicitly teaching comprehension monitoring and debugging metacognitive strategies; (c) being more aware of their role in their students' cognition and metacognition; and (d) using problem solving style as a way to gauge level of physics knowledge. High school physics teachers may want to consider increasing their focus on the planning stage of problem solving when working with their students. Students in this study, as well as previous studies (Phang, 2009, 2010), used cognition and metacognition more in the planning stage than any of the other problem solving process. This creates an opportunity for teachers to pause their students and encourage reflection and comprehension monitoring. Teacher led questioning and probing has been found to encourage students metacognitive use (Wade-James et al., 2018). This may also help students shift their focus which is typically on getting an answer and not understanding the underlying concepts (Lucas & Lewis, 2019).

With an increased focus in reflection during the planning phase, this could mean that high school physics teachers will need to explicitly teach metacognitive strategies to help students more successfully reflect, monitor their comprehension and debug in the case of dissatisfaction. It is recommended that teachers teach both the components and meanings of the different metacognitive strategies (Avargil et al., 2018). Students are more likely to engage in metacognitive strategies if those strategies have been directly taught to them (Dimmitt & McCormick, 2012). Since this study has highlighted the importance of comprehension monitoring and debugging on conceptual change, it is highly suggested that teachers incorporate strategies for those specific processes into their physics problem solving lessons. Additionally, metacognitive skills are interdependent (Veenman & Spaans, 2005), so explicitly working on comprehension monitoring and debugging will also help students use other metacognitive strategies.

The emergent themes that came out of the think aloud brought to light the influence that teachers have on their students' cognition and metacognition while solving physics problems. Participants noted both positive and negative thoughts about the strategies their teachers taught them and the expectations for showing their work. Most notably, the participants did not always see the value in or understand the reasoning for using the strategies their teacher had asked them to use. Nadelson et al. (2018) included teachers in the social, cultural, and community factors that influence a student's motivation to engage in the conceptual change process. Teachers should consider how their expectations and requirements both shape their student's understanding of physics concepts and affect their student's willingness to engage with their own understanding.

In addition to teacher influence, another theme that came from the think aloud is the participants' use of common sense or logic while solving physics problems. High school physics students come to their first class with a wealth of physics knowledge and physics related experiences (Disessa, 1996; Gunstone et al., 1992; von Aufschnaiter & Rogge, 2010; Vosniadou, 1994). What was evident from the think aloud data is that not all participants viewed those experiences as valid physics knowledge. While it is true that not all prior knowledge that students bring to the classroom fully aligns with the scientifically accepted physics concept (Disessa, 1996; Eryilmaz, 2002; Gunstone et al., 1992; Posner et al., 1982; Sherin, 2006; Taasoobshirazi & Sinatra, 2011; von Aufschnaiter & Rogge, 2010; Vosniadou & Mason, 2012), it is still important to recognize and address student prior knowledge (Banilower, 2019). Teachers could help students find value in and build from their prior knowledge, to assimilate their knowledge, rather than try to replace, or accommodate, their prior knowledge. By validating the students' prior experience with physics content, students may become more confident in their physics understanding and more willing to engage with their conceptions.

And lastly, high school physics teachers may be able to use their students' problem solving styles as a way to gauge the students' levels of physics knowledge expertise. The participants in this study who use a hybrid approach, using both conceptual and computational knowledge to solve the problems, answered more questions correctly, similar to the finding in previous studies examining the differences between expert and novice physics problem solvers (Kohl & Finkelstein, 2008; Larkin, 1979). A student's ability to answer a physics problem correctly does not necessarily mean that the student also understands the underlying concepts (Nandagopal & Ericsson, 2012) and likewise, a student with a strong conceptual understanding is more equipped to choose the necessary tools to solve a physics problem (Kuo et al., 2013). A teacher may be able to understand more about the students' level of understanding from how they approach the problem than if they get the problem correct.

Limitations

The mixed methods design of this study provided quantitative and qualitative data about how high school physics students use cognition and metacognition while solving physics problems. Due to the small sample size of this study, seven participants, it is difficult to extend the conclusions to a larger population of high school physics students. Additionally, while the sample included participants with a range of demographic information, it is not a representative sample of high school physics students.

The methods of the study have their own limitations. Think aloud interview protocols allow researchers to hear the participants thought processes but are limited to the thought processes the participant share with the researcher (Ericsson & Simon, 1993; van Someren et al., 1994). The participants may not have felt comfortable sharing all of their thoughts, thereby limiting the robustness of the think aloud interview data. When coding the results of the think aloud interviews, there is a close, dependent relationship between cognition and metacognition making it sometimes difficult to distinguish (Veenman et al., 2006). To help account for this, clear code definitions were developed (Appendix G).

Finally, doing the study during the COVID-19 pandemic provided additional limitations. Due to the COVID-19 pandemic, the schools that the participants attended stopped in person school in March of 2020. The participants would have had a varied experience with their physics classes from March 2020 until the end of their school year. With the think aloud interviews occurring from June 2020 to August 2020, it is possible that participant had not studied physics in three to five months. Lana noted “I have not partaken in any physics since, ah, March”. Many of the participants commented on how long it had been since they have studied physics, causing them feel “a little rusty on physics” (Ellie). For instance, Aaron commented,

> Reading this, I feel like in, in mid, mid school, like before we got out for quarantine, I could definitely solve this like, right off the top of my head. I wouldn't even have to look at the equation sheet. I can do it. And this is, it's taking me so much longer, because I have to, like, basically reteach myself everything that I forgot since school let out.

Participants may have shared different problem solving strategies had they been actively engaged in a physics class at the time of the study.

When the in person schooling ended for the participants in March 2020, many students experiences virtual classes. Since the participants were used to interacting through a virtual platform, the use of Webex did not seem to affect the participants willingness to share their thoughts and created more flexibility for scheduling interviews. One limitation of the virtual nature of the interview was that I had a limited view of the participant and their work. When a participant looked “off screen” I could not see what they were looking at unless they shared out loud what they were doing. If the interviews were done in person, I would have had a full view of their work.

Future Research

This study investigated how high school physics students use cognition, use metacognition, and voice dissatisfaction while solving physics problems through the lens of conceptual change. This endeavor aligned with both Hammer et al. (2005) and

Ranellucci et al.'s (2013) recommendations that research should look at processing, cognitive engagement, and metacognitive engagement in terms of how students further their learning. Based on the results of this study, the following are recommendations for future research.

In this study, participants were more likely to use metacognition, specifically comprehension monitoring, early in the problem solving process when they are setting up the problems and choosing a concept or equation to solve the problem. Research should look to investigate how including a reflection step in the physics problem solving process after or during the planning phase would change student use of metacognition. The problem solving processes typically taught in high school physics classes and textbooks includes checking (evaluation) at the end of the problems solving process, but does not explicitly have students check their work (monitoring) during the problem solving process (Etkina et al., 2014; Knight, 2013). Gunstone et al. (1992) highlighted the importance of having students engage in metacognition, as students who are engaged in metacognition are likely to engage in a stronger conceptual change process. By including a step in the problem solving process that encourages and reminds students to reflect and monitor their comprehension, the likelihood of students engaging in conceptual change may increase; when students do engage in the conceptual change process, it may have a larger effect.

Participants in this study shared both internal and external dissatisfaction, but only debugged following external dissatisfaction. Aaron and Lana both indicated that they would normally use strategies to debug that were not available in the think aloud interview. It is possible that the participants would have shared and engaged with their dissatisfaction differently if they were in their typical high school physics setting. Further research may look at how high school physics students express dissatisfaction, both internal and external, in their natural physics classroom setting and how they debug as a result of that dissatisfaction. Finding dissatisfaction with their physics knowledge is the key first step in the conceptual change process (Dole & Sinatra, 1998; Posner et al., 1982). By better understanding how students express dissatisfaction and move on in the conceptual change process as a result, researcher and teachers may be able to find ways to help students embrace and debug their dissatisfaction.

In the emergent codes from the think aloud interview, participants noted that hey use different cognitive and metacognitive strategies when they are working on problems on an assessment compared to problems on a practice or homework set. Motivation to engage and approach goal orientation both play into a student's decision to engage in conceptual change (Dole & Sinatra, 1998; Taasoobshirazi et al., 2016; Taasoobshirazi & Sinatra, 2011; Nadelson et al., 2018). The participants' comments could indicate that if they see the physics problems as different tools depending on the context, their likelihood to engage in conceptual change may be different for those different contexts. Further research could investigate how the different physics problem contexts, practice and assessment, affect a student's engagement in conceptual change.

The results from this study suggest that physics students' problems solving style may indicate their level of physics content knowledge. Since this study did not formally assess physics content knowledge and was limited by its small sample size, further research would be needed to confirm the relationship. An interesting follow up to this study would be to have participants complete the Force Concept Inventory (Hestenes et al., 1992) prior to completing the think aloud to better understand how level of conceptual physics knowledge relates to problem solving type. By further understanding how problem solving style plays into level of physics content knowledge (expertise), teacher may be able to better assess their students' level of understanding.

Appendix A

Parental Consent Form

HIGH SCHOOL STUDENTS USE OF METACOGNITION IN PHYSICS PROBLEM SOLVING

INFORMED CONSENT FORM

RESEARCH PROCEDURES
This research is being conducted to better understand how students use cognition and metacognition while solving physics problems. If you agree to allow your child to participate, your child will be asked to fill out a questionnaire about how they approach physics problems and then they will be asked to think aloud while they solve physics problems during an interviewed. I want to collect data on their thought processes while solving physics problems. This interview will occur using the Webex virtual meeting space and will be audio/video recorded. The entire process should take 50 minutes to an hour.

RISKS
There are no foreseeable risks for participating in this research.

BENEFITS
There are no benefits to you or your child as a participant other than to further research in physics education.

CONFIDENTIALITY
The data in this study will be confidential. Your child's name will only be used to match their work with consent and assent forms. Once all data are collected, the student names will be removed and replaced with a pseudonym. Only the researcher will have access to the key connecting student names and pseudonyms that will be kept in a password protected computer. The recordings will also be kept on a private computer that is password protected and only the researcher will have access to them. After five years, the recordings will be deleted. The de-identified data could be used for future research without additional consent from participants. The Institutional Review Board (IRB) committee that monitors research on human subjects may inspect study records during internal auditing procedures and are required to keep all information confidential.

While it is understood that no computer transmission can be perfectly secure, reasonable efforts will be made to protect the confidentiality of your transmission. Those who participate via WebEx may review Cisco's website for information about their privacy statement https://www.cisco.com/c/en/us/about/legal/privacy-full.html.

PARTICIPATION
Participants must be students who are currently taking or previously enrolled in an Algebra I based high school physics class. Your child's participation is voluntary, and you may withdraw your child from the study at any time and for any reason.

CONTACT
This research is being conducted by Stephanie Stehle with the College of Education and Human Development at George Mason University. She may be reached at (724) 355-7227 for questions or to report a research-related problem. Her advisor, Erin Peters-Burton with the College of Education and Human Development at George Mason University can be reached at (703) 993-9695. You may contact the George Mason University Institutional Review Board office at (703) 993-4121, or IRB@gmu.edu, if you have questions or comments regarding your or your child's rights as a participant in the research.

IRB: For Official Use Only

George Mason University
Institutional Review Board

Project Number: 1615059-1

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This research has been reviewed according to George Mason University procedures governing your or your child's participation in this research.

CONSENT

I have read this form, all of the questions I have at this time have been answered by the research staff, and I agree to allow my child to participate in this study.

____   ____________________

Signature   Date of Signature

____

Name of child

Appendix B

Student Assent Form

HIGH SCHOOL STUDENTS USE OF METACOGNITION IN PHYSICS PROBLEM SOLVING

ASSENT FORM

My name is Stephanie Stehle and I am from George Mason University's College of Education and Human Development.

I want to talk to you about a research study I am doing. In my study, I want to learn more about how physics students think while solving physics problems. Your parents have already agreed that you may take part in the study, so feel free to talk with them about it before you decide whether you want to join the study.

What will happen to me in the study?
I would like you to participate because you are currently enrolled in a High School physics class. If you would like to participate in the study, you will be asked to answer a questionnaire about how you approach physics problems and then you will be asked to think aloud while solving physics problems during an interview. I am interested in collecting data on your thought processes while solving physics problems. This interview will occur using the Webex virtual meeting space and will be audio/video recorded. The entire process should take 50 minutes to an hour.

What are the risks?
There are no risks associated with participation in this study.

What are the benefits?
There are no benefits to participating in this study.

Will anyone know that I am in the study? (Confidentiality)
Your information will not be shared with anyone. Your name will only be used to match consent forms, assent forms, and assessments. Once all data are collected, your name will be removed and replaced with a pseudonym. Only the researcher will have access to the key connecting your name and pseudonym that will be kept in a password protected computer. The recordings will also be kept on a private computer that is password protected and only the researcher will have access to them. After five years, the recordings will be deleted.

What if I do not want to participate or decide later to withdraw?
Being in this study is voluntary. You don't have to be in this study if you don't want to or you can stop being in the study at any time.

Will I receive anything for being in the study?
There is no compensation for participating in this study.

Who can I talk to about this study?
If you have questions about the study or have any problems, you can talk to you parents, or call Erin Peters-Burton (703) 993-9695, the Principal Investigator for this study. If you have questions about the study but want to talk to someone else who is not a part of the study, you can call the Institutional Review Board office at George Mason University at (703) 993-4121 or IRB@gmu.edu.

IRB: For Official Use Only

George Mason University Institutional Review Board

Project Number: 1615059-1

Page **1** of **2**

Your signature below means that you have read the above information about the study, have had a chance to ask questions to help you understand what you will do in this study, and you are willing to be in the study. Your signature also means that you have been told that you can change your mind later if you want to.

____ ________________
Child's Name (printed) and Signature Date

Appendix C

Demographic Information

Please answer the following questions about yourself. Your name will only be used to verify your consent and assent forms are turned in. It will not be used for any other purposes.

First Name: __________________________ Last Name: _________________________
Age: __________

Gender Identification (Please choose one):
- ☐ Male
- ☐ Female
- ☐ Another identity
- ☐ Prefer not to respond

Race/Ethnicity (Please choose one):
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African-American
- ☐ Hispanic or Latino
- ☐ Native Hawaiian or other Pacific Islander
- ☐ White
- ☐ Two or more races
- ☐ Other
- ☐ Prefer not to respond

Grade during the 2019-2020 School Year (Please choose one):
- ☐ 9
- ☐ 10
- ☐ 11
- ☐ 12

Physics Course (Please choose one):
- ☐ Physics
- ☐ Honors Physics
- ☐ AP Physics 1
- ☐ Other ____________________

High School: ____

Mathematics Class during the 2019-2020 School Year (Choose all that apply):

- ☐ Geometry
- ☐ Algebra 2
- ☐ Pre-Calculus/Trig
- ☐ Calculus
- ☐ AP Calculus AB
- ☐ AP Calculus BC
- ☐ Statistics
- ☐ AP Statistics
- ☐ Not currently enrolled in a mathematics class
- ☐ Other ____________________

Appendix D

Physics Metacognitive Inventory

In order to better understand how you solve problems in physics, please respond to each of the following statements from the perspective of: When solving physics problems…

		Never true of myself 1	Rarely true of myself 2	Sometimes true of myself 3	Usually true of myself 4	Always true of myself 5
1	I think about what a physics problem is asking before I begin to solve it.	☐	☐	☐	☐	☐
2	While solving a physics problem, I ask myself periodically if I am meeting my goals.	☐	☐	☐	☐	☐
3	I ask for help when I don't understand a physics problem.	☐	☐	☐	☐	☐
4	I draw free-body diagrams to help me solve physics problems.	☐	☐	☐	☐	☐
5	I am a good judge of how well I solve physics problems.	☐	☐	☐	☐	☐
6	When solving physics problems, I know how I work best.	☐	☐	☐	☐	☐
7	When solving physics problems, I have a specific purpose for each strategy I use.	☐	☐	☐	☐	☐
8	I go back and check my work after solving a physics problem.	☐	☐	☐	☐	☐
9	After solving a physics problem, I double check my answer.	☐	☐	☐	☐	☐
10	I use free-body diagrams to help me solve physics problems.	☐	☐	☐	☐	☐
11	When solving a physics problem, I know how to apply a strategy to successfully solve the problem.	☐	☐	☐	☐	☐
12	When solving a physics problem, I know why I'm using a particular strategy.	☐	☐	☐	☐	☐
13	When solving a physics problem, I know when to use a particular strategy.	☐	☐	☐	☐	☐

		Never true of myself 1	Rarely true of myself 2	Sometimes true of myself 3	Usually true of myself 4	Always true of myself 5
14	Before solving a physics problem, I think about what a reasonable value for the answer would be.	☐	☐	☐	☐	☐
15	While solving a physics problem, I ask myself questions about how well I am doing.	☐	☐	☐	☐	☐
16	While solving a physics problem, I periodically evaluate how well I am doing.	☐	☐	☐	☐	☐
17	After solving a physics problem, I look back to see if I did the correct procedures.	☐	☐	☐	☐	☐
18	I know why free-body diagrams are important for physics problem solving.	☐	☐	☐	☐	☐
19	Before I start solving a physics problem, I plan out how I'm going to solve it.	☐	☐	☐	☐	☐
20	Before solving a physics problem, I identify all the important parts of the problem.	☐	☐	☐	☐	☐
21	While solving a physics problem, I ask myself if I am meeting my goals.	☐	☐	☐	☐	☐
22	I seek help when I don't understand the physics problems that I am solving.	☐	☐	☐	☐	☐
23	I draw free-body diagrams for the physics problems I am solving.	☐	☐	☐	☐	☐
24	Before solving a physics problem, I eliminate information in the problem that I don't need.	☐	☐	☐	☐	☐
25	After solving a physics problem, I look back at the problem to see if my answer makes sense.	☐	☐	☐	☐	☐
26	I change strategies when I fail to solve a physics problem.	☐	☐	☐	☐	☐

Appendix E

Physics Problems for Think-Aloud

Think aloud examples.

1. Five people were eating apples, A finished before B, but behind C. D finished before E, but behind B. What was the finishing order?

2. What day comes three days after the day which comes two days after the day which comes immediately after the day which comes two days after Monday?

The following questions test your knowledge of mechanics content knowledge: kinematics and forces. Please answer each question to the best of your ability. You may use a calculator and the equations provided.

While you are working on the three problems, I want you to think aloud. This means that any thought you have while working on the problem, no matter how unimportant you may think the thought is, you are to say out loud.

Equations:

$g = 9.8 \text{ m/s}^2$

$v = v_o + at$

$x = x_o + v_o t + \frac{1}{2}at^2$

$v^2 = v_o^2 + 2a\Delta x$

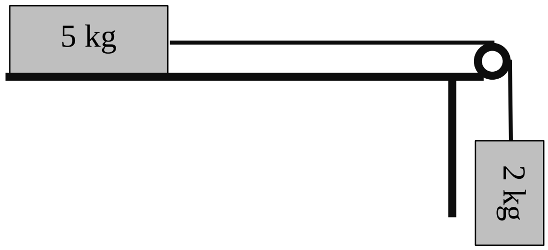
$\Sigma F = ma$

$F_f \leq \mu F_N$

$a_c = v^2/r$

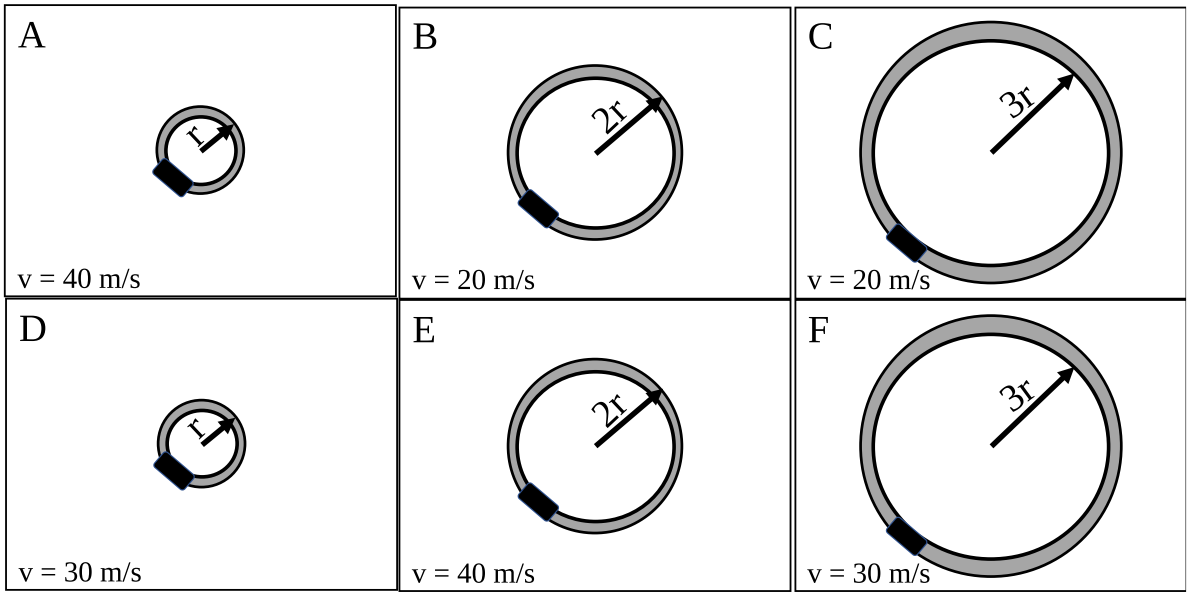
1. Cooper and Zoe are standing on a balcony on the second floor of building. They are 6 m above the ground. At the same time that Cooper drops a ball, Zoe throws a ball straight up with a speed of 5 m/s.
    a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.
    b. Who's ball hits the ground first?
    c. How much time passes between the first and second balls hitting the ground?

2. A block of mass 5 kg is sitting on a table. The 5 kg mass is connected to a 2 kg mass, which is hanging off of the table, by a massless string that runs over a frictionless pulley. (See picture below.)



   a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.
   b. Assume the table is frictionless, what is the acceleration of the blocks?
   c. Assume the table is not frictionless, what force of friction is required to keep the system moving at a constant velocity?

3. In each case below, a small car is traveling around a circular track at a constant speed. The radii of the tracks and the speeds of the cars are given for each case.



a. Before you start working on the problem, draw a conceptual model for the problem. A conceptual model is a visual representation that shows the concepts you use to know and understand the thing you are trying to represent.
b. Rank the magnitude of the net force acting on the cars on these tracks.
Greatest 1_____ 2_____ 3_____ 4_____ 5_____ 6_____ Least
OR, _____ The magnitude of the net force on the cars is the same but not zero for all these tracks.
OR, _____ The magnitude of the net force on the cars is zero for all these tracks.
OR, _____ We cannot determine the ranking for the magnitude of the net force on the cars.

Please explain your reasoning.

Appendix F

Scripts for Data Collection

1. Once students are in the virtual meeting room and settled in an area of their home where they can work: *Thank you for participating in my research project. The questionnaire that you are about to take has two sections. The first section asks information about you. Your name will not be used in the research. It is being used to match your survey with your assent and consent forms. The second section asks you about your use of 26 strategies for solving a physics problem. Please answer the questions to the best of your ability. If you have any questions, please ask.*
2. Once students have completed the questionnaire: *I am going to ask you to work on three physics problems. While you are working on the three problems, I want you to think aloud. This means that any thought you have while working on the problem, no matter how unimportant you may think the thought is, you are to say it out loud. I want to understand your thought process while working on physics problems. Before I have you work on the physics problems, I am going to demonstrate a think aloud for you and have you practice thinking aloud while completing a puzzle. If at any time you want to stop participating in the study, you are welcome to do so. Do you have any questions for me before we begin?*
3. I will first demonstrate a think aloud while completing the first non-physics related puzzle.

4. I will then ask the student to practice the think aloud while completing the second non-physics related puzzle: *On the next page is another logic puzzle. I would like you to practice thinking aloud by completing the puzzle. While you are working, please say everything that goes through your mind.* Once the student has completed their practice think aloud: *Do you have any questions for me before we begin?*
5. Once the practice problem is done, and the student has no more questions: *In your packet are three physics problems. Please work through them one at a time. While you are working, please say every thought that goes through your mind. You may use a calculator and the given equations if needed.*
6. While the student is working on the physics problem, I will only interrupt the student's work if they have stopped talking out loud. If that is the case, I will say: *please say everything that goes through your mind* or *keep talking*.
7. Once they are done with the problems: *Thinking across all of the problems, is there anything in particular that you noticed about how you solve problems?*
8. Once they are done: *Thank you for your participation. If you have any questions, please let me know. If you could please take a picture or scan of your work and email it to me, I would greatly appreciate it.*

Appendix G

A Priori Codebook with Examples

Parent Code	Child Code	Grandchild Code	Definition	Examples
Problem Solving	Reading		Participant is reading the problem.	"How much time passes between the first and second ball in the ground?"
		Rereading	Participant is rereading the problem, or a part of the problem.	"So, (re-reads question a quick pace) how much time passes between the first and second ball? Um, so first Cooper, is the first."
	Planning	Drawing Picture or FBD	Participant is gathering, organizing, and analyzing information to be able to solve the problem by drawing a picture or diagram.	"I would draw one block I would draw the same thing, ah, as the image above. (pause) Keeping, ah, the table so I'm gonna draw a line underneath. The five kilogram box, I'll put five kg inside this box. Two kg in this box. Ah, I'm gonna have a downward facing arrow with the acceleration going nine point eight."
		Arranging Information	Participant is gathering, organizing, and analyzing information to be able to solve the problem by arranging information.	"And I made sure that the normal force and the force of gravity the arrows are the same length, because the forces are acting with the same magnitude."

Parent Code	Child Code	Grandchild Code	Definition	Examples
Problem Solving	Planning	Listing Knowns & Unknowns	Participant is gathering, organizing, and analyzing information to be able to solve the problem by listing knowns and unknowns.	“but we aren't giving force and we aren’t. Well, we actually need force, yeah, I'm going to solve for the variable a.”
		Choose Concept or Equation	Participant is gathering, organizing, and analyzing information to be able to solve the problem by choosing a concept or equation.	“So, we would do sum of the forces right? Equals mass times acceleration.”
	Calculating		Participant is performing the mathematics needed to solve the problem such as solving for an unknown and plugging in numbers.	“Two kilograms, two times nine point eight equals nineteen point six”
	Answering		Participant is stating their answer to the problem.	“Then the time would be one point one seconds for Cooper’s ball.”
	Checking		Participant is making sure that their work or answer makes sense/is correct.	“zero point four. Is my coefficient of friction, which makes sense, because you always want something that's less than one.”
Metacognition – Knowledge of Cognition	Declarative		Participant makes a statement about themselves as a learner, their strategies, or what conditions impact their performance.	“I’m overthinking.”

Parent Code	Child Code	Grandchild Code	Definition	Examples
Metacognition – Knowledge of Cognition	Procedural		Participant makes a statement about how to do the task.	"Okay, so it's the same thing I would do with Cooper"
	Conditional		Participant makes a statement as to when or why it is appropriate to use declarative and procedural knowledge.	"but instead of putting the negative sign, (inaudible) get rid of it because I notice that both sides have negative and negative divided by negative is gonna make positive."
Metacognition – Regulation of Cognition	Planning	Strategy	Participant is selecting a strategy prior to working on a task.	"So I know that I need to find the amount of time it takes Cooper's ball to hit the ground and the amount of time that it takes Zoe's ball to hit the ground. And then I'm gonna subtract those answers, to find the amount of time in between them."
		Allocating Resources	Participant is allocating resources prior to working on a task.	"Okay, I'm just looking through the equations right now."
		Goal Setting	Participant is setting goals prior to working on a task.	"We're finding net force acting on the cars on these tracks greatest to least."
	Information Management		Participant uses a strategy to help them be more effective in their efforts.	"So I'm, I'm just gonna redraw it for my own sake. Sometimes that helps me. (pause while drawing) Five kilograms. (pause while drawing)"

Parent Code	Child Code	Grandchild Code	Definition	Examples
Metacognition – Regulation of Cognition	Comprehension Monitoring		Participant makes a real time assessment of their progress, comprehension, or goals.	“I don't know if that's right.”
	Debugging		Participant uses a strategy to fix errors or alter learning.	“Can you define the, the meaning of the word new force because that may have slipped my mind. I'm wrong.”
	Evaluation		Participant evaluates their work or answer once it is completed.	“zero point four. Is my coefficient of friction, which makes sense, because you always want something that's less than one.”
Teacher Influence or Expecations			Participant mentioned their teacher.	“my teacher always told me to write, ah, meters per second square next to it and I never did and I probably should, but I really, I don't see the point in it.”
Problems as Assessments			Participants shared how they would approach the problems it were on an assessment.	“Um, nineteen point six, we'll just leave it blank and miss a point, if this was a test.”
Common Sense or Logic			Participant explicitly shares that they are using common sense or logic as part of their reasoning.	“I can probably just put down a general answer based on logical reasoning instead of actually putting it down.”

Appendix H

Excerpts from Think Aloud Interview Coded with Emergent Codes

Teacher Influence or Expectations
"Also like what information do I need, um, in the problem that could make me answer the problem quicker. Cause like, sometimes if it was like, a trick question, um I know my teacher did that a lot this year, um, to make sure we were really reading it. So, I have learned to like make sure I read each problem carefully and then, like, double checking my work, I guess." (Catherine)
"Okay, um, then you already know, I have not partaken in any physics since ah March, and while I did very well in that class, it was mostly because it was very, like, it was a very easy class to pass because I had a very good table partner. We're very smart together. We worked well together and my teacher kinda just like, let us copy off of each other. So, (laughs) like, legitimately, we'd be taking a quiz and everybody in in our little for like, four person table groups would just look at each other and be like, what'd you get? Is this like, are we all on the same page here? Okay, cool. That's fit (laughs) and such. But I think that honestly it made all of us a little bit smarter, because we all pay attention more and like helped each other." (Lana)
"Wait, (pause) ah, no no no. What I've been taught because I'm also thinking I know I've been taught to, ah, isolate, you know, the variable first before plugging in numbers. Um, I personally don't see the, I personally prefer just plugging the numbers in and isolating from there. So, I'm just do what I would normally do, and just plug in the numbers." (Samir)
"Well, my teacher always taught me, first like, organize your key variable set up because I know I noticed for the first problem I did it the way I would normally do it. And I was contemplating doing it the way that my teacher would do it. I realized that's not something I would do outside of a testing environment. So, I'm gonna stick to what I normally do, which is, you know, just plug in the numbers and solve for the variable instead of solve for the variable and then plug in the numbers. So that's one thing I noticed." (Samir)
"I figure out problems the exact way my teacher taught me, which was to kind of look at what you have, and look where you need to be and kind of wiggle your way through that, whether it's going a little bit backwards to forwards or forwards to backwards. And another thing I noticed is having to jump through hoops like, trying to, especially looking at the equation sheet trying to figure out is there anything that just gets me a straight answer? Is there anything where I kind of need to piece things together where I need to be? Stuff like that." (Jessica)
"Yeah, my, my teacher had us do this all the time. Like, whenever we did problems, she would have us go up on the board, write them down, and explain to the class how we did it. So, this is like, second nature for me now." (Aaron)
"my teacher always told me to write, ah, meters per second square next to it and I never did and I probably should, but I really, I don't see the point in it." (Aaron)

Teacher Influence or Expectations
"Um, which is something that my teacher had us do all the time. She would just have this re, redo what was there. Um, and I don't, I still don't understand why. (laughs)" (Aaron) "One thirty three point three, three, three. Um, point three, three we'll just rounded to two decimal places in this one because it doesn't tell me how far to round and I don't wanna use sig figs because, I don't." (Aaron) "So, when I've, I noticed that, I look at what I have, what what is given to me, you know, I I look at like, so on tests and stuff for like, in school, she gives us equation sheets and they usually only have the equations that we're using on them. So I feel like I tried to do that with this, and I don't know if I got them all right but I, I definitely tried to use process of elimination and and try and figure out like the quickest way to get to where the answer here." (Aaron) "I wouldn't think it would be zero, because that's just kinda seems pointless as a question in general. Like, I wouldn't expect them to give me such an easy answer. So, I'm going to cross that one out." (Judy) "that's never an option because that is a tricky one with easy way out for students like me, who don't know what's going on" (Judy)

Problems as Assessments
"I don't know, I think that's all. I, I know I don't really check my work. Like, if it was a test, I would, um (pause) I don't know, I never really run the numbers again, but I would just look over it and make sure it makes sense again before I moved on to the next problem. But otherwise if it's not like an exam, I'm not really a work checker." (Ellie) "Well, my teacher always taught me, first like, organize your key variable set up because I know I noticed for the first problem I did it the way I would normally do it. And I was contemplating doing it the way that my teacher would do it. I realized that's not something I would do outside of a testing environment. So, I'm gonna stick to what I normally do, which is, you know, just plug in the numbers and solve for the variable instead of solve for the variable and then plug in the numbers. So that's one thing I noticed." (Samir) "Usually, if I were doing a problem like this, like, if I had this on the test, I'm skipping this problem. I'm going right to the next one, um, because this is like, me, not studying for like a week. And this is a really big test." (Aaron) "Calm down, this isn't a test, you said that. I don't know, I don't know. I just need to calm down and do some physics." (Aaron) "So we'll just say, for the sake of just getting an answer, which is what I would do on tests, all the time. And sometimes it would be right. And I would just be very happy." (Aaron) "Um, nineteen point six, we'll just leave it blank and miss a point, if this was a test." (Aaron)

Problems as Assessments
"So, when I've, I noticed that, I look at what I have, what what is given to me, you know, I I look at like, so on tests and stuff for like, in school, she gives us equation sheets and they usually only have the equations that we're using on them. So I feel like I tried to do that with this, and I don't know if I got them all right but I, I definitely tried to use process of elimination and and try and figure out like the quickest way to get to where the answer here." (Aaron) "So, I think I would probably leave this if I was, if I were doing a test, because at least I showed some effort. So here's my attempt at consoling myself and I would submit this, as it is right now." (Judy)

Common Sense or Logic
"Then I also tried to use, like, logic like, does this makes sense, I guess. Just trying to remember everything. Like, little like tricks that I learned, I guess, in class" (Catherine) "Does that make sense?" (Lana) "I tried to apply logic to all of them. Like, what like, my own knowledge on, like, how objects interact with each other and gravity around them in the forces that I know exist. Um, and also, I feel like, I was thinking about, like, if I were the person doing this kind of so, like with Cooper and Zoe's problem. Like, if I were there with my brother, and we dropped a ball and throw it up, like, what would actually happen? Like, how would I imagine that playing out? Um, and just like, I guess I just got that from my general knowledge of the world, I feel like, I knew that the ball, like Cooper's ball would hit the ground first because not because of the actual physics behind it, but because of my general knowledge of the world, and I knew that that ball is gonna hit the ground first. I just had to figure out how I knew that." (Lana) "Yes, I hope that this helped you in some way, because I feel like it wasn't real physics. It was just my brain talking about the logic behind things." (Lana) "So initially, just common sense wise, I'm thinking that Cooper's ball is gonna hit the ground first, because they're both standing in the same location but Cooper's just dropping it straight down whereas Zoe is throwing it up initially. So common sense wise I know that my answer should be Cooper. Um, it says to explain my answer." (Ellie) "Um, now this time, because I know that there is, um, acceleration and I know that like, logically, it's gonna accelerate with the two kilogram um mass falling down and that's pulling the five kilogram mass right. Well, like, logically, speaking, I know that the gravity is gonna make the two kilogram mass fall down." (Ellie) "So, then I'm thinking, does that logically make sense two point eight meters per second squared. I think, yeah, that it makes enough sense, I guess. So, that's my final answer for part B, two point eight meters per second square." (Ellie) "I think I like to be. I mean, I guess everybody's logical in solving physics problems, but I feel like I tackle it in a logical way. And then I also try to think, so like, I try to make sure I'm not

Common Sense or Logic
getting too caught up in, like, the physics of it that I'm forgetting, like, the way the real world works. And, like, does it actually make sense." (Ellie) "I don't know, I think that's all. I, I know I don't really check my work. Like, if it was a test, I would, um (pause) I don't know, I never really run the numbers again, but I would just look over it and make sure it makes sense again before I moved on to the next problem. But otherwise if it's not like an exam, I'm not really a work checker." (Ellie) "Logically I would think that Cooper's ball would hit the ground first, because Zoe's would have to travel upwards and then downward." (Judy) "I can probably just put down a general answer based on logical reasoning instead of actually putting it down." (Judy) "My reasoning is that, okay, (writes while explaining reasoning) my reasoning is based off of process of elimination as well as logical reasoning, um, concerning, um, extreme values within a set. I determined the value places based, or wait no. I determined the value places." (Judy) "I think I'm gonna leave that one alone because I can just justify it with logical reasoning and then." (Judy)

Appendix I

Excerpts from Think Aloud Interview Coded as Statements of Dissatisfaction

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Lana	was reading problem 1	Reading	I'm not much of a thought process	self	gave an answer to 1B using reasoning	Answering
Lana	was reading problem 1C	Reading	I'm assuming there's actual physics work that needs to be done there. (laughs, pause, puts hand on face/chin) Um. (sigh) Oh, okay, well, without actually remembering, like the actual equations, and how I would actually find the answer this	self	reasoned through the concepts she would need to take into consideration to solve the problem	Planning - choose a concept or equation
Lana	was reasoning through the concepts she would need to take into consideration to solve the problem	Planning - choose a concept or equation	which is very conceptual and I'm confused by it already	self	decided that she would not get an actual answer	Answering

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Lana	was reasoning through the concepts she would need to take into consideration to solve the problem	Planning - choose a concept or equation	I'm not gonna get an actual answer	self	continued to reason through the concepts she would need to take into consideration to solve the problem	Planning - choose a concept or equation
Lana	was giving a conceptual answer to 1C, using hand motions for a concept she could name	Answering	I forget the word for that words	self	moved on with her explanation or reasoning	Answering
Lana	was reading problem 2	Reading	Uh, working on physics problems after this one really tells me how little I retained the information I learned in class. (laughs) Like, maybe if I had my notes, I'd be able to answer this question, like accurately.	self	reread problem 2B	Reading
Lana	was reading problem 2C	Reading	I see what I did here.	self	corrected her conceptual answer to problem 2B	Answering
Lana	was answering problem 2C	Answering	Um, but that's just my (turns page) hypothesis.	self	moved on to problem 3	Move on
Lana	was reading problem 3B	Reading	What?	information	asked for clarification and then reread the problem	*Reading

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Lana	was answering problem 3B	Answering	Um, and my thought process behind that I'm not entirely sure honestly,	self	went on to explain her reasoning for 3C	Answering
Lana	was answering problem 3C	Answering	It really sounds like I just have no idea what's going on. I feel like I have no grasp on anything.	self	continued to share her reasoning for 3C	Answering
Judy	was reasoning through problem 1B	Planning - choose a concept or equation	I'm also gonna look at these equations to see if there's anything that I can use to help me since I don't really know.	self	looked at equations	Planning - choose a concept or equation
Judy	was listing knowns and unknowns for the problem	Planning - list knowns and unknowns	I'm right now confused about what I'm supposed to do	self	decided to answer the question with logic	Planning - choose a concept or equation
Judy	was reading problem 1C	Reading	Well, I'm also not sure how to do that either. Because, a lot of these, er, some of these equations I haven't seen before.	self	reread the problem	Reading
Judy	was re-reading problem 1C	Reading	Yeah, I don't understand this one, so	self	moved on to problem 2	Move on
Judy	was looking for equations to answer 2B	Planning - choose a concept or equation	We aren’t given any velocities. I don't see. Hum	information	reread the problem	Reading
Judy	was looking for equations to answer 2B	Planning - choose a concept or equation	I don't think I know how to solve this one either.	self	moved on to problem 2C	Move on

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Judy	was reading problem 2C	Reading	So, I'm kind of confused by this one because, when asked for what force of friction is required to keep the system moving, I'm wondering if it's asking for a specific type of force of friction or if its asking for a numerical value.	information	decided to solve it numerically	Planning - choose a concept or equation
Judy	was looking at the equation sheet	Planning - choose a concept or equation	I can't figure out what the quantitative and I, I don't really have any other options to solve it, for now I would just probably (short pause) leave it blank and then come back to it.	self	moved on to problem 3	Move on
Judy	was reading problem 3	Reading	Um, for a conceptual model, I wouldn't really know how to do this one because I'm just used to drawing free body diagram	self	decided that it was a circular motion problem	Planning - choose a concept or equation
Judy	was comparing the magnitudes of the velocities and radii of the cars in problem 3	Planning - list knowns and unknowns	So, at this point it's just me making an educated guess and once I can figure out what's in my brain right now how to find which one has the greatest magnitude and remember what magnitude was	self	decided to eliminate other options and then guess	Planning - choose a concept or equation
Judy	was looking at possible equations for problem 1B	Planning - choose a concept or equation	And I'm thinking about what each of the equations actually mean and I don't seem to understand it. So, I think I would probably leave this if I was, if I were doing a test, because at least I showed some effort. So here's my attempt at consoling myself and I would submit this, as it is right now.	self	decided that she was done, she did as much work on the problems as she could	Move on
Samir	was looking at the equation sheet	Planning - choose a concept or equation	Is X to be distance by the way? For the equation sheet?...Okay. Just make sure. And initial velocity and final velocity. So final velocity is v and the initial was supposed to v o. Right?	information	asked me for clarification then made notes on his paper	*Planning - arranging information

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Samir	was reading question 3B	Reading	Wait, does this mean I only have to answer one of these.	information	asked me for clarification then reasoned out the problem conceptually	*Planning - choose a concept or equation
Samir	was answering question 3B	Answering	Can you define the, the meaning of the word new force because that may have slipped my mind. I'm wrong.	self	asked me for clarification the continued with his answer to 3B	*Answering
Catherine	was reading question 3	Reading	Um, what do I need to know to determine the ranking of the magnitude (pause) of the net force?	information	started to reason out problem 3 conceptually	Planning - choose a concept or equation
Catherine	was reasoning out problem 3 conceptually	Planning - choose a concept or equation	Why do I, why do I need to know the radius of the track.	information	looked at equation sheet	Planning - choose a concept or equation
Catherine	was plugging numbers into an equation	Calculating	I don't know if I need to use that, do that with these. (pause while writing) Nine hundred r. Ok, I don't know if I'm going to need to use those. I don’t think I will.	information	continued to plug numbers into equation	Calculating
Aaron	was looking at the equation sheet	Planning - choose a concept or equation	V equals vo, Ah, is that the original, v initial?	information	asked me for clarification then picked an equation	*Planning - choose a concept or equation
Aaron	was solving an equation for an unknown	Calculating	Wait, we're looking for, hold on...Okay. Yeah. So stop. What are you doing?	self	reestablished what he is solving for and looked at equation sheet	Planning - list knowns and unknowns

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Aaron	was looking at the equation sheet	Planning - choose a concept or equation	Um, I'm trying to think about (pause) how to, to solve is this. It's been. Usually, if I were doing a problem like this, like, if I had this on the test, I'm skipping this problem. I'm going right to the next one, um, because this is like, me, not studying for like a week. And this is a really big test. (pause) Um (pause) kay. Calm down here	self	reestablished knowns and unknowns and looked at equation sheet	Planning - list knowns and unknowns
Aaron	was re-establishing knowns and unknowns and looking at equation sheet	Planning - list knowns and unknowns	Wait, or, or is nine point eight meters per second squared acceleration? (looking at equation sheet) Accel, or no, velocity. Velocity has (pause) um, so need to remember the difference now, because it's been it's been so long since I've done this between acceleration. I think meters per second is just acceleration. Velocity is meters per second squared.	self	looked at equation sheet	Planning - choose a concept or equation
Aaron	was calming self down and started writing information down	Planning - arranging information	I'm pretty sure and you know what, I'm just gonna take a guess, because I'm not one hundred percent sure	self	picked an equation to use	Planning - choose a concept or equation
Aaron	was calculating answer on calculator	Calculating	Nine point eight times six. That's not the right thing. Six. Then we get fifty-eight point eight, which seems like a very big number. Um, but that's the only thing that I have right now.	self	created a scenario where the answer would make sense	Checking

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Aaron	was stating his answer	Answering	Well that wouldn't make sense. Why would we, I don't, you wouldn't be multiplying something. Nine point eight meters per second squared would have to be the acceleration, not the velocity because meters per second, you would have to multiply meters per second by meters per second to get, a squared. Right? So then that can't be the acceleration. That's why it's such a big number because I just did a nothing problem. And now I'm going to erase it because it means nothing. (Loud breath out).	self	reread the question	Reading
Aaron	was plugging numbers into an equation	Calculating	But then I'm just mul, dividing and I'm just gonna get six. So that doesn't make sense. (sigh) So, then velocity final, when it's, must be, no. (pause) So, ooo talking her out here, I feel like I'm just confusing myself and that I should just get an answer.	self	decided to keep answer and move on to 1C to see if it will help him answer 1B	Move on
Aaron	was discussing how he can move on to 1C before answering 1B	Move on	I can't remember any other equations and I don't see any other equations that could help me on the sheet.	self	picked an equation to use	Planning - choose a concept or equation
Aaron	was plugging numbers into an equation	Calculating	So it's just gonna be v, v ini, v final would be the same. Um, which I don't think makes sense, but that's what we got. Fifty-eight point eight. Um. And then we'll divide that all by nine point eight, because that's what we chose to use for the acceleration but that's, that's not correct.	self	used the number he has and continues to solve the problem	Calculating

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Aaron	was reading problem 2	Reading	Reading this, I feel like in, in mid, mid school, like before we got out for quarantine, I could definitely solve this like, right off the top of my head. I wouldn't even have to look at the equation sheet. I can do it. And this is, it's taking me so much longer, because I have to, like, basically reteach myself everything that I forgot since school let out.	self	continued reading problem 2	Reading
Aaron	was starting to write down an equation to solve 2B	Planning - choose a concept or equation	so wait you're looking for the acceleration of the blocks. (pause) Um, so, like block, I would probably ask my teacher, like the acceleration of both blocks. Like, would you want the acceleration of the two kilogram block? And then, what is the acceleration of the five kilogram block if the second block is pulling it? Or I would just sit here and I would think about, does that even make sense? What if their the same thing and then I would probably just do the problem the whole way through. And figure it out, which is what I'm gonna do, I'm gonna figure out if, and if they're different, then I'll be like, okay, obviously it wants two different ones.	information	decided to figure it out as he is going	Planning - choose a concept or equation
Aaron	was calculating an answer to 2B	Calculating	Nope. That's not right. That doesn't seem correct though ok.	self	went back to a previously attempted approach	Calculating

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Aaron	was writing an answer to 2B	Answering	Would it just be kg over meters, or kg, kilograms per meters per second square, that doesn't seem to make sense for the value for force.	self	decided he would miss a point on a test, moved on, and then remembered the unit	Move on
Aaron	was discussing the knowns and unknowns for 2B	Planning - list knowns and unknowns	That's two kilogram block. (pause) But it's pulling that, so wouldn't that, why did I, why did I find the force.	self	looked at equation sheet	Planning - choose a concept or equation
Aaron	was recalling the equation for the force of friction	Planning - choose a concept or equation	We're, we're just gonna move on from question A question B right now. Because I can't remember why I did that, and maybe whenever I go through the second question, it'll help me like just regroup. And I feel very chaotic right now	self	returned to recalling equations	Planning - choose a concept or equation
Aaron	was looking at the equation sheet	Planning - choose a concept or equation	Uh, ac, that's something different, equals v two divided by r. Ac, ac, ac, it stands for the acceleration something, accelerations. (pause and makes clicking noises) Acceleration, that it's acceleration something, it's acceleration.	self	explained what the other variables are in the equation	Planning - list knowns and unknowns
Aaron	was solving for the acceleration of two of the cars	Calculating	We find acceleration there's n-, there probably is that I'm missing something.	self	decided to solve for acceleration for the rest of the cars	Planning - choose a concept or equation
Aaron	was checking to make sure there was not another way to solve the problem	Checking	Acceleration is. It's, it's AC, I know it's acceleration something. Don't remember what the c is.	self	restated what the problem is asking for and gave his answer	Answering

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Jessica	was reading question 1C and looking at the equation sheet	Reading	I feel like, I don't have enough information for this one, just because it doesn't tell me how long it's going up with a speed of five meters per second before it starts going back down again	information	looked at the equation sheet again and then moved on to problem 2 (she returned to the problem after the interview and solved the problem)	Move on
Ellie	was drawing a conceptual model/free body diagram for 3A	Planning - draw a picture or diagram	Um, ok, to be honest, this free body diagram is probably incorrect, the only force that I can think of right now, acting on the, um (pause) acting on the cars is just. I'm gonna draw a dot representing the car and I'm going to draw an arrow pointing inward, for um, the centripetal force. I guess. I don't know if that's right. (pause) Centripetal force, ok	self	moved on to 3B	Move on
Ellie	was giving the reasoning for her answer to problem 3C	Answering	My reasoning that it's zero for all of these tracks is, it's said, in the description that the radii of the tracks and the speeds of the cars are, are no, it said traveling around a circular track at a constant speed. Oh wait. Okay. Okay. Now I've changed. I changed my mind because, um (pause) it's a constant speed, which is true. However, the velocity is not constant because travelling in a circle, so it's constantly changing direction. So the velocity is not constant. So, um, I know the net force can't be zero.	self	decided to solve for force and redo 3B	Planning - choose a concept or equation

Participant	Action Prior to Statement	Problem Solving Process Prior	Statement of Dissatisfaction	Self or Info Provided	Action After Statement	Problem Solving Process After
Ellie	decided to solve for force and redo problem 3B	Planning - choose a concept or equation	Um. So now I'm gonna try to think. What, what (inaudible) okay. I’m trying to remember the equation used for, going back to the equation sheet.	self	looked at equation sheet	Planning - choose a concept or equation

* Participant engaged in debugging in addition to the problem solving process.

Appendix J

IRB Approval Letter

Office of Research Integrity and Assurance

Research Hall, 4400 University Drive, MS 6D5, Fairfax, Virginia 22030
Phone: 703-993-5445; Fax: 703-993-9590

DATE:	June 8, 2020
TO:	Erin Peters-Burton
FROM:	George Mason University IRB
Project Title:	[1615059-1] High School Physics Students Use of Metacognition in Physics Problem Solving
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	June 8, 2020
REVIEW TYPE:	Expedited Review
REVIEW TYPE:	Expedited review category #7

Thank you for your submission of New Project materials for this project. The George Mason University IRB has APPROVED your submission. This submission has received Expedited Review based on applicable federal regulations.

Please remember that all research must be conducted as described in the submitted materials.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding followed by a signed consent form unless the IRB has waived the requirement for a signature on the consent form or has waived the requirement for a consent process. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Federal regulations require that each participant receives a copy of the consent document.

Please note that any revision to previously approved materials must be approved by the IRB prior to initiation. Please use the appropriate revision forms for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others and SERIOUS and UNEXPECTED adverse events must be reported promptly to the IRB office. Please use the appropriate reporting forms for this procedure. All FDA and sponsor reporting requirements should also be followed (if applicable).

All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to the IRB.

This study does not have an expiration date but you will receive an annual reminder regarding future requirements.

Please note that all research records must be retained for a minimum of five years, or as described in your submission, after the completion of the project.

Please note that department or other approvals may be required to conduct your research in addition to IRB approval.

If you have any questions, please contact Katie Brooks at (703) 993-4121 or kbrook14@gmu.edu. Please include your project title and reference number in all correspondence with this committee.

GMU IRB Standard Operating Procedures can be found here: https://rdia.gmu.edu/topics-of-interest/human-or-animal-subjects/human-subjects/human-subjects-sops/

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within George Mason University IRB's records.

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Biography

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