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## ACCEPTANCE

This dissertation, INVESTIGATING INDIVIDUAL DIFFERENCES IN THE CONCEPTUAL CHANGE OF BIOLOGY MISCONCEPTIONS USING COMPUTER-BASED EXPLANATION ACTIVITIES, by MERRIN OLIVER, was prepared under the direction of the candidate's Dissertation Advisory Committee. It is accepted by the committee members in partial fulfillment of the requirements for the degree, Doctor of Philosophy, in the College of Education and Human Development, Georgia State University.

The Dissertation Advisory Committee and the student's Department Chairperson, as representatives of the faculty, certify that this dissertation has met all standards of excellence and scholarship as determined by the faculty.

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Merrin Oliver

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INVESTIGATING INDIVIDUAL DIFFERENCES IN THE CONCEPTUAL CHANGE OF  
BIOLOGY MISCONCEPTIONS USING COMPUTER-BASED EXPLANATION  
ACTIVITIES

by

MERRIN OLIVER

Under the Direction of Maggie Renken, Ph.D.

ABSTRACT

The current study examined the effects of computer-based self-explanations (i.e., generated by the learner) and instructional explanations (i.e., provided to the learner) on undergraduate biology students' revision of photosynthesis and respiration misconceptions. Individual differences, particularly students' prior knowledge, significantly impact the effectiveness of instructional tasks. Oftentimes, an instructional task is effective only for learners at a particular prior knowledge level. Cognitive Load Theory suggests that too much or too little instructional support can overwhelm a learner's working memory. When used for building knowledge, self-explanations and instructional explanations, like those employed in the current study, both interact with prior knowledge. Prior research has indicated that instructional explanations may only benefit students with low prior knowledge, and self-explanations may

only benefit students with high prior knowledge. The current study addressed whether such effects extend to the use of explanation tasks to facilitate knowledge revision, in which existing misconceptions are revised. Four hundred and thirty eight undergraduate major and non-major biology students completed an online activity for course credit. Participants were randomly assigned to one of three conditions (self-explanation, instructional explanation, or no explanation) and then prompted with a set of photosynthesis questions, each of which was followed by their assigned instructional task and a cognitive load measure. One week later, participants returned to the activity to take a posttest. Results indicated students entered the activity with high rates of photosynthesis and respiration misconceptions. Further regression analyses indicated that only self-explanations, not instructional explanations, increased learning compared to no explanations. Trends in effect sizes suggest self-explanations only benefited students with sufficient prior knowledge. Higher cognitive load was associated with less learning in both explanation conditions, but not in the no explanation condition. The current results suggest that self-explanations may effectively promote knowledge revision, assuming students are familiar with the content, while instructional explanations may not foster knowledge revision in a computer-based setting. Implications for adaptive instruction that targets knowledge revision are addressed.

**INDEX WORDS:** Conceptual change; Misconception; Cognitive load; Prior knowledge; Self-explanation; Learning; Instruction



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ACTIVITIES

by

MERRIN OLIVER

A Dissertation

Presented in Partial Fulfillment of Requirements for the

Degree of

Doctor of Philosophy

in

Educational Psychology

in

Educational Psychology, Special Education, and Communication Disorders

in

the College of Education and Human Development

Georgia State University

Atlanta, GA  
2017

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## DEDICATION

I would like to dedicate this dissertation to my amazing parents, Gail and Joe. They always told me that they would support me while I was in college and have kept their word through all *twelve years*. This dissertation is as much of a result of their hard work as it is mine. I love you guys, thank you.

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## **INDIVIDUAL DIFFERENCES IN CONCEPTUAL CHANGE: A REVIEW OF EXPERTISE AND COMMITMENT**

Learning is a complex interaction between learners' existing knowledge and the new information they are learning (Posner, Strike, Hewson, & Gertzog, 1982; Dochy, Segers, & Buehl, 1999). The prior knowledge students bring into a classroom affects how they process incoming information (Dole, 2000; Pintrich, Marx, & Boyle, 1993). Accurate prior knowledge facilitates learning (Alexander & Murphy, 1999; Chi, 1978), whereas inaccurate knowledge hinders learning (Alvermann & Hague, 1989; Dole, 2000; Guzzetti et al., 1993; Pintrich, Marx, & Boyle, 1993; Sinatra & Pintrich, 2003). Knowing this, educators and researchers alike focus on understanding the knowledge structures that students bring with them into the classroom, with a particular interest in inaccurate prior knowledge, otherwise known as misconceptions (Posner, Strike, Hewson, & Gertzog, 1982).

Misconceptions occur when an individual's prior knowledge conflicts with the knowledge currently accepted by experts in the domain (Braash, Goldman, & Wiley, 2013; Tippet, 2010) and generally refer to erroneous knowledge held by a learner. Because of the broad and somewhat segmented nature of the literature addressing erroneous knowledge, misconceptions may also be referred to as alternative frameworks (Driver & Easley, 1978), alternative beliefs (Tippet, 2010) alternative conceptions (e.g., Garnett, Garnett, & Hackling, 1995), preconceptions (e.g., Clement, 1993), naïve conceptions (Reiner, Slotta, Chi, & Resnick, 2000), preinstructional beliefs (Chinn & Brewer, 1993) or inaccurate ideas (e.g., Kendeou & van den Broek, 2007). Specific definitions of misconceptions and their alternative terms often times vary depending on the scope of the inaccuracy they aim to describe or the inaccuracy's origin

(Duit & Treagust, 2003). For instance, a misconception could be at the statement level (e.g., bats are blind), while other misconceptions may be at the conceptual level (e.g., plants suck food in through their roots). Additionally, some misconceptions may arise due to previous exposure to misinformation (e.g., seeing a cartoon where an ostrich buries its head in the sand), while others develop intuitively based on learners' personal experiences (e.g., thinking the earth is flat, because the ground looks relatively flat every time you see it). With this in mind, this review will use the term "misconception" to generally refer to erroneous knowledge of various grain sizes and origins. Further, I refer to the correction of misconceptions as revision and the process of revision as conceptual change. The various levels of misconceptions, as well as the conceptual change process that facilitates revision, are further defined and discussed later in this review.

The most notable characteristic of misconceptions is that they are hard to correct with instruction (Chi, 2005) and are therefore often described as being strong and robust. Research indicates prevalent misconceptions in domains like history (e.g., Leinhardt & Ravi, 2008), psychology (e.g., Taylor & Kowalski, 2004), politics (e.g., Nyhan & Reifler, 2010) and science (Wandersee, Mintzes, & Novak, 1994). For instance, even after instruction, psychology majors tend to incorrectly believe that humans only use 10% of their brain (Higbee & Clay, 1998), or that people diagnosed with schizophrenia have multiple personalities (Taylor & Kowalski, 2004). Misconceptions are perhaps the most prevailing in science (Chi, 2005), because learners enter the classroom with intuition- or experience-based ideas about how the world works (Dole, 2000; Guzzetti, 2000). Similar science misconceptions are found in learners across all ages (Tippet, 2010), illustrating their prevalence and resistance to instruction. For instance, the misconception that the seasons are caused by the earth's distance from the sun is typically first documented in kindergarten (Phillips, 1991) and is still endorsed by learners during and after

college (Cordova, Sinatra, Jones, Taabsoobshirazi, & Lombardi, 2014; Phillips, 1991; Schneps & Sadler, 1989). Due to the commonplace nature of misconceptions in learning science, most of the research on misconceptions has been, and still is, based in science domains (Chi, 2013).

Since misconceptions are common, but detrimental, to learning, decades of research have sought to understand the process of misconception revision and the factors that affect a learner's ability and willingness to revise. Theory and empirical evidence from educational psychology, cognitive psychology, developmental psychology, and science education converge to provide insight into the process of knowledge revision, broadly known as conceptual change. While a great deal of conceptual change research investigates the design of text-based instruction which aims to facilitate revision (see Guzzetti, 2000 and Tippet, 2010 for reviews), conceptual change research has not been applied to the new age of computer-based adaptive educational technologies, like adaptive courseware or intelligent tutoring systems. These adaptive technologies optimize learning outcomes across students by utilizing algorithms to dynamically adapt to individual differences in how students are performing in online learning environments (SRI, 2016). These systems model and respond to learning by measuring changes in error rates (VanLehn, 2006) – however, intelligent tutor systems model processes of knowledge building, not conceptual change, and have only recently moved towards distinguishing between errors due to lack of knowledge and errors due to incorrect knowledge (i.e., misconceptions; Durkin & Rittle-Johnson, 2015; Liu, Patel, & Koedinger, 2016).

An important next step is applying conceptual change research findings and theory to the design of adaptive educational technologies. Bridging the gap between conceptual change research and adaptive technologies could not only potentially increase conceptual change in domains like science, but might also increase the fit, and thus capability, of adaptive technology

models (Liu, Patel, & Koedinger, 2016). Conceptual change theory and findings provide insight into the process of revision and how learners' individual differences can affect this process. For instance, current text-based instructional methods used to facilitate conceptual change are effective for some learners, but not all (Guzzetti, 2000). Adaptive technologies could potentially detect misconceptions and adapt instruction to facilitate revision, and more specifically adapt that instruction to learner characteristics that interact with the revision process. I review studies that highlight the effects of individual differences on conceptual change, focusing specifically on the effects of expertise and commitment, because measures of these characteristics could be collected and adapted to in computer-based environments and are not bound to classroom contexts (Limon, 2001). In the sections that follow, focused reviews of expertise and commitment are prefaced with a discussion of conceptual change theory and followed by recommendations for adaptive courseware design.

### **Conceptual Change**

Students naturally interpret new information according to what they already know. They do not enter into learning situations as blank slates, but instead bring with them knowledge from both informal and formal learning experiences (Murphy & Mason, 2006). However, often the knowledge that learners bring with them is unsophisticated or inaccurate, making it necessary to correct that knowledge through conceptual change before it can be used to support further learning. Conceptual change is broadly understood as the process of correcting and restructuring old knowledge in light of new knowledge. It includes both outdated incorrect prior knowledge and updating it with the incorporation of new, correct information (Kendeou & O'Brien, 2014), thereby leading students from less to more sophisticated conceptions (Krueger, Loughran, & Duit, 2002). Conceptual change theory emerged out of a need to understand how knowledge

changes through different developmental stages. The distinction between knowledge building and knowledge revision was initially outlined in Piaget's concepts of assimilation and accommodation (1974). Assimilation is a process of knowledge building in which learners apply what they already know to new phenomenon in an effort to make sense of it. Accommodation is a process of knowledge revision, where learners must revamp their existing knowledge, because it conflicts with new information, or is insufficient to understand that new information. Following Piaget's discussion of accommodation, a cognitive approach to conceptual change emerged (Carey, 1985; Posner et al., 1982; Chi, 1992; Vosniadou & Brewer, 1992). This approach uses frameworks from developmental psychology and science education to explain how increases in domain knowledge require structuring of that knowledge as it grows, and why that knowledge is often so resistant to necessary change in educational contexts. In order to understand why knowledge often resistant to revision, it is necessary to understand what misconceived knowledge looks like.

### **What Constitutes Conceptual Change?**

Two broad schools of thought address and qualify the nature of misconceptions. The first school describes that misconceptions are coherent, but inaccurate, explanatory frameworks operating within a learner's knowledge structure to generate predictions about phenomena (Posner et al., 1982). In other words, misconceptions are flawed mental models that produce consistent errors (Vosniadou, 1994). A mental model is a collection of knowledge positions that make up a concept, and thus a flawed mental model contains multiple incorrect propositions that support each other (Chi, 2013). Successful revision would result in restructuring the flawed mental model so that the original misconception no longer exists in the knowledge structure.

The second school of thought describes misconceptions as fragmented and incomplete knowledge structures that simply need to develop sufficient structure (diSessa, 1983; Gillespie & Esterly, 2004). In this case, successful revision would not erase the initial misconception but would reassign that piece of knowledge so that it is no longer used the same way. Current theory supports that initial misconceptions continue to coexist with new, updated knowledge (Kendeou & O'Brien, 2014). Further, fMRI evidence demonstrates that even after a misconception is revised through instruction, it is still activated and has to be inhibited during problem solving (Foisy, Potvin, Riopel, & Masson, 2015; Masson, Potvin, Riopel, & Foisy, 2014). Essentially, these two schools of thought diverge on the scope of misconceptions and what happens to the misconception after it is revised. Does an entire mental model need to be corrected to fix the misconception, or does only a piece need to be corrected? More recent theory argues that these schools of thought are not mutually exclusive; misconceptions can be big or small – but the key characteristic is they represent inaccurate knowledge, not missing knowledge (Chi, 2008).

Although the terms *misconception* and *conceptual change* both appear to convey a misunderstanding or change at the concept level, the terms are broadly used to describe knowledge at various grain sizes. Conceptual change theories have always acknowledged the distinction between more shallow changes and more radical changes. Shallow change, in which the knowledge is incorrect because it is *inaccurate* (Chi, 2013), requires changing the values in a proposition or the relationship between two propositions (e.g., “normal science” in Kuhn, 1993; and “regular learning” in Carey, 1988). Radical conceptual change, in which the knowledge is incorrect because it is *incommensurate* with the correct information (Chi, 2013), would require changing the nature or the properties of the concepts themselves (Carey, 1988). To understand how the change process will vary according to the scope of the misconception, Chi (2008, 2013)

described three different levels of conceptual change: belief revision, mental model transformation, and categorical shifts.

Belief revision is the smallest grain size and is necessary when the learner's misconception is contained to a single fact or belief. A belief is a piece of knowledge at the statement level (e.g., bats are blind). The need for belief revision is evident when a learner consistently endorses his or her false belief, and the misconception can be rectified by revising the incorrect belief. Typically, instruction that explicitly refutes the misconception (e.g., bats are not blind) with the correct information (e.g., bats can see very well, and in some cases, see better than humans) is used to facilitate revision of misconceptions at this level. While refutations are the most successful instructional method for revising false beliefs, they do not work all the time (e.g., Guzzetti, 2000; Tippets, 2010).

Mental model transformation is the next level of conceptual change and is necessary when the mental model representing a concept is flawed. In this situation, the misconception *is* at the concept level. A flawed mental model contains multiple false beliefs which support each other. The need for mental model transformation is evident when a learner consistently generates inaccurate predictions or explanations about a concept (Chi, 2008) For example, a student with a flawed mental model of the concept of plant metabolism might believe that plants get the food needed for growth from minerals and water in the soil, that photosynthesis uses energy from the sun to turn that food into energy, and subsequently that plants do not respire. Conceptual change instruction can promote mental model transformation by revising all the false beliefs associated with the mental model. This conceptual change process is considered to be more difficult than revising only a single false belief.

Finally, categorical shifts are the largest scale of conceptual change and are necessary when a learner incorrectly categorizes an overarching concept as the wrong kind (i.e., category mistake). The need for a categorical shift is evident when a learner misunderstands ontology, like understanding heat as a substance or entity, instead of a process (Chi, 2008). Category shifts cannot be achieved through the revision of false beliefs. Rather, it is a more complex conceptual change process that involves reassigning the concept to a different category (of which may or may not already exist in knowledge), thus changing the dimensions of that concept. The primary purpose of the levels Chi (2008, 2013) outlined was to explain why some misconceptions are more resistant to change than others; the difficulty of achieving conceptual change increases with the grain size of the misconception (Vosniadou & Brewer, 1992). Additionally, these levels also serve to clearly demonstrate the breadth of what constitutes as conceptual change and what constitutes as a misconception. Although there are various levels of conceptual change, the literature reviewed later in this paper focuses on conceptual change at the levels of belief revision and mental model transformation. The complexity of the conceptual change process associated with category shifts has limited its research to qualitative and case base studies, thus making this type of conceptual change outside of the scope of a review of empirical research.

### **The Process of Conceptual Change**

A landmark paper by Posner, Strike, Hewson, and Gertzog (1982) was the first to address what specific conditions are needed for conceptual change to occur. First, the learner must be dissatisfied with his prior conception; he must realize that his prior knowledge is not sufficient to solve a problem or understand a new phenomenon. Second, the new conception must be intelligible; the learner must be able to comprehend the new information enough to realize its utility for fixing the problems incurred by the initial conception. Third, the new conception must



be plausible; the learner must perceive it as being reasonable according to their prior knowledge. Fourth, the new conception must appear useful for understanding other phenomenon; the learner must see the fruitfulness of the new information beyond the current problem at hand. Posner and colleagues proposed that if any of these four conditions are not met, conceptual change is unlikely (1982).

If the conditions for conceptual change are not met, how do learners respond to conflicts with their prior knowledge and incoming knowledge? Chinn and Brewer (1993) outline seven different types of responses that are observed in students learning science. Four of the possible responses describe ways in which the learner can respond without changing: they can simply ignore the information, find a reason to reject the information, decide to deal with information later, or rationalize that the new information does not apply to their prior conception. The last three response types describe ways in which the learner can accept the data: they can accept but reinterpret the new information so it no longer conflicts with their prior conception, they can accommodate the new information by making small, or peripheral, changes to their prior conception, or they can accommodate the new information by making fundamental changes to their prior conception. Only the last response type would be considered conceptual change, illustrating why the likelihood of revision using normal instruction is low (Tippet, 2010).

Co-activation and cognitive conflict, although not always specifically referred to using those terms, are two primary requisites for conceptual change (Alvermann & Hague, 1989; Chan, Burtis, & Bereiter, 1997; Chi, 2008; Dole and Sinatra, 1998; Hewson & Hewson, 1984; Guzzetti, 2000; Kendeou & O'Brien, 2014; Limon, 2001, van den Broek & Kendeou, 2008). Co-activation occurs when both the learner's misconception and the new information are simultaneously activated in working memory (e.g., by reading one after the other in a text; Kendeou & O'Brien,

2014). A cognitive conflict occurs when the learner is aware of a conflict between his prior knowledge and the new information (Chi, 2008). Co-activation is necessary for a cognitive conflict to occur, but not always sufficient to achieve it (van den Broek & Kendeou, 2008). Alvermann & Hague (1989) demonstrated this finding early on in conceptual change research using different variations of a text. One version of the text stated both the misconception and the correct knowledge, while the other version also stated both the misconception and correction knowledge but explicitly pointed out the conflict between them. Students were only able to overcome their misconception and comprehend the content from the text when the second version, which explicitly pointed out the conflict, was used. Thus, co-activation alone was not enough; students needed to be made aware of the conflict with the co-activated information.

While co-activation and cognitive conflict significantly increase the likelihood of revision, they are not always enough (Chan, Burtis, & Bereiter, 1997; Guzzetti, 2000). Even when students encounter conflicting information, they may be content with their now apparent misconception (Chan, Burtis, & Bereiter, 1997); all six of the non-revision responses outlined by Chinn and Brewer (1993) occurred after students were aware of the conflict. Students must be motivated to revise their misconception (Pintrich, Marx, & Boyle, 1993). Further, even if a student is motivated to revise and does so, the old misconception is not erased or lost from memory (diSessa, 2013). That misconception will continue to be activated, especially if the misconception is newly revised (Kendeou & O'Brien, 2014), and so the learner must learn to inhibit responses based on the misconceived knowledge (Foisy, Potvin, Riopel, & Masson, 2015; Mason, Potvin, Riopel, & Foisy, 2014). Thus, the process of successful revision includes 1) co-activating the misconception and correct conception, 2) realizing the conflict between the information, 3) outdating the misconception, 4) updating knowledge with the correct conception,

5) continuing to use the correct conception and not resorting back to the misconception. Learner characteristics can affect a learners' likelihood for revision at various points in the conceptual change process, thus providing a number of opportunities for instruction to adapt and overcome known misconceptions. However, conceptual change instruction has not taken advantage of these opportunities for adaptation, mostly because empirical research which investigates the effects of specific learner characteristics on conceptual change is limited (Lin, Yen, Liang, Chiu, & Guo, 2016). The following sections review the existing research in order to provide recommendations for the adaptation of conceptual change instruction.

### **The Effects of Individual Differences**

The likelihood of revision depends on characteristics of learners' prior knowledge, including both characteristics of their particular misconception and characteristics of the knowledge structure in which the misconception is embedded (Braash, Goldman, & Wiley, 2013; Chinn & Brewer, 1993; Dole & Sinatra, 1998). However, synthesizing results on individual differences across different studies is difficult, because researchers distinguish among these characteristics differently (Dole & Sinatra, 1994). Despite this, practically overlapping definitions of terms can be collapsed to discuss main tenets that should be considered when trying to design adaptive conceptual change instruction. The effects of expertise, or the amount of prior domain knowledge the learner has, is considered by most conceptual change theories to have significant effects on a learner's *ability* to revise (Chinn & Brewer, 1993; Dole & Sinatra, 1998). Additionally, the effects of commitment, or how resistant learners are to giving up their misconception, is considered to have significant effects on learners' *willingness* to revise (Chinn & Brewer, 1993; Dole & Sinatra, 1998). These two factors are the focus of the discussion that follows, because they can be measured using the types of data already collected in adaptive

educational technologies and are not bound to classroom contexts (Limon, 2001). It is important to note that research demonstrates the importance of other factors, especially when trying to facilitate conceptual change in a classroom settings, like the learners' epistemic goals, (Chinn & Brewer, 1993; Vosniadou, 1994), their self-efficacy or interest (Cordova et al., 2014; Pintrich, Marx, & Boyle, 1993), and other motivation-related factors (Pintrich, Marx & Boyle, 1993).

### **Expertise**

Learners' level of expertise significantly affects subsequent learning. Expertise is generally defined as the accumulation of prior knowledge which results in capabilities such as skills and understanding (Chi, 2006). Thus, learners' level of expertise is synonymous with their level of prior knowledge. When reading textbooks, students with higher levels of prior knowledge understand and remember information better than students with lower levels of prior knowledge (Kendeou & van den Broek, 2005). These interactions between expertise and knowledge building (i.e., without revision) are well understood in the literature (e.g., Kalyuga, Chander, & Sweller, 1998; McNamara & Kintsch, 1994), and studies now address how these interactions might vary across different types of instructional tasks (i.e., expertise reversal effects; Kalyuga, 2007; Sweller, 2008). However, the relationship between expertise and conceptual change is less understood.

Conceptual change research refers to learners' expertise levels in terms of prior knowledge, background knowledge, content knowledge, domain knowledge, or achievement. Specific definitions of these terms, and subsequently their measures, vary across studies. Some consider it to be the amount of scientific knowledge the learner has which is not tied to the misconception in question (Chinn & Brewer, 1993), or the amount of knowledge the learner has regarding a specific topic (Boscolo & Mason, 2003); while others generally define it as the

extent of knowledge in any particular field (Alexander, 1992), or how much a student has achieved academically in that domain (Yin et al., 2016).

Another approach to conceptualizing levels of expertise is to consider the quality, not quantity, of the learner's domain knowledge. The quality of a learner's knowledge represents the amount and nature of connectivity in the learner's knowledge structure, not necessarily the number of propositions. Early work by Mathew (1982) suggests that high knowledge learners have different knowledge, not necessarily more knowledge, which is more readily available than the knowledge of novices. Along this line, the notions of well-developed schemas, (Crocker, Fiske, & Taylor, 1984; Schauable, Glaser, Ragavan, & Reiner, 1991), coherent conceptions (Braash et al., 2013; Thargard, 1992), and strong conceptions (Dole & Sinatra, 1998) all describe the rich, well-connected domain knowledge structures that are associated with expertise. Further, research indicates that experts organize their knowledge hierarchically, where pieces of knowledge are chunked together into categories and organized according to their relationships (Chi, Glaser, Farr, 2014); whereas novices are thought to have fragmented and less-organized structures (Chi, Hutchinson, & Robin, 1989).

Conceptual change theory suggests that both low expertise and high expertise can be detrimental to conceptual change processes (Chinn & Brewer, 1993), and alludes a level of expertise that is *just right* for revision. If learners' do not have sufficient prior knowledge, they will have a hard time detecting and understanding the cognitive conflict (Limon, 2003). If learners have too much prior knowledge, it will be easier for them to explain away the new information (Chinn & Brewer, 1993). Specifically, experts can use their extensive knowledge to discredit or reinterpret the new information; because their misconceptions are thought to be more deeply entrenched in their well-organized knowledge structures, they may be particularly

inclined to do this instead of revising (Chinn & Brewer, 1993; Crocker, Fiske, & Taylor, 1984; Dole & Sinatra, 1998; Thargard, 1992; Vosniadou, 1994). However, only one study could be found that empirically demonstrates a relative disadvantage for high levels of prior knowledge. In their study, Cordova and colleagues (2014) investigated conceptual change of seasonal changes in high school students. The high domain knowledge group had relatively no changes in misconception rates after reading a refutation text, whereas the low knowledge group did have significant reductions in misconceptions.

Conversely, the negative effects of low domain knowledge are better established by the literature. Across high school students (Limon & Carretero, 1997; Linnenbrink-Garcia, Pugh, Koskey, & Stewart, 2012) and undergraduate students (Braash, Goldman, & Wiley, 2013), low domain knowledge learners are less prone to conceptual change than high domain knowledge learners. Additionally, conceptual change may decay more over time for low domain knowledge learners than high domain knowledge learners (Cordova et al., 2014; Linnenbrink-Garcia et al., 2012). Low knowledge learners are at a disadvantage, because sufficient domain knowledge is necessary to notice a conflict in contradicting information; otherwise learners will not detect a need to change (Limon & Carretero, 1997). Limon (2003) posits that a certain level of domain knowledge is needed for the learners to compare and evaluate information in order to identify which knowledge in particular needs revision. Without adequate understanding of the conflict, the learner is likely to simply ignore or exclude the new information (Chinn & Brewer, 1993). However, even when learners have that conflict explicitly pointed out with a refutation, they may not understand the conflict enough to resolve it (Limon, 2003).

Braash et al., (2013) provides an activation-based account for the negative effects of low domain knowledge on conceptual change. They theorize that low knowledge learners are less

likely to achieve co-activation and cognitive conflict, because information activated in fragmented knowledge structures decays quickly. This shallow and quickly-decaying activation makes low knowledge learners less able to simultaneously process the new information and misconception, leaving them unable to generate a coherent representation of the new knowledge through revision. Conversely, activation of coherent misconceptions (associated with high knowledge learners) will persist for longer, because the activation will spread through more connections in the knowledge structure. This more elaborate activation should make manipulating the various conceptions in working memory easier, and also allow for deeper processing during encoding.

In addition to learners with low knowledge levels potentially having their working memory overloaded, they may not be good at self-regulating their learning either; whereas high knowledge learners are better able to self-regulate their own learning (Chi, Glaser, & Farr, 2014; Ertmer & Newby, 1996; Limon, 2003). Self-regulation includes the ability to evaluate one's own knowledge (Kruger & Dunning, 1999), a skill critical to achieving conceptual change. Further, high knowledge learners may be able to inhibit the use of old, outdated misconceptions more so than learners with low levels of knowledge (Foisy, Potvin, Riopel, & Masson, 2015; Mason, Potvin, Riopel, & Foisy, 2014; Kendeou & O'Brien, 2014).

Motivational factors may be able to compensate for the negative effects of low domain knowledge. In two studies, students who scored high in motivational factors like self-efficacy and interest, but low in domain knowledge, achieved more conceptual change in science than students with the same low knowledge levels but low motivation scores (Cordova et al., 2014; Linnenbrink-Garcia et al., 2012). Interestingly, in Linnenbrink-Garcia and colleagues (2012) study, high motivation only mitigated the negative effects of low prior knowledge for girls, not

boys (2012). In most cases, levels of domain knowledge are positively related to motivation (Dole & Sinatra, 1998; Johnson, 1994; Limon, 2003), and topic interest (Tobias, 1994) and so learners with high expertise are already benefiting from high motivation. Overall, conceptual change research indicates that learners with low levels of expertise are less able to revise their misconceptions, and they may be less motivated to do so.

### **Commitment**

While only one study indicates relatively negative effects of having expertise, theory suggests that any negative effects of expertise would be due to their commitment to the misconception (Chinn & Brewer, 1993; Crocker, Fiske, & Taylor, 1984; Dole & Sinatra, 1998; Thargard, 1992; Vosniadou, 1994). While learners with sufficient levels of domain knowledge have the ability to revise their misconceptions, they may not be willing to. The more committed learners' are to their misconception, the more resistant they will be to revision. It is clear, both intuitively and theoretically, that commitment has a significant impact on conceptual change, but it is a difficult construct to measure directly (Dole & Sinatra, 1998). In addition to providing insight to learners' likelihood to revise, commitment may also demonstrate the conceptual change process (Taylor & Kowalski, 2004), with levels of commitment to misconceptions dropping as knowledge is being outdated, and levels of commitment to the new knowledge increasing as it is updated. With such measure, conceptual change process can be tracked before it has been objectively achieved.

Although commitment is a seemingly broad construct that is reportedly difficult to quantify directly, research investigates a number of factors that can serve as proxies to indicate learners' levels of commitment. For instance, some researchers investigate commitment by asking learners how confident they are in the accuracy of their misconception (Dole &



Niederhauser, 1990, as cited in Tippet, 2009) – high levels of commitment are indicated by high self-reported levels of confidence. Others investigate commitment by measuring the learner’s belief, or agreement with, the new (i.e., accurate) information (Murphy & Alexander, 2004; Renken & Nunez, 2013; Taylor & Kowalski, 2004). Belief and confidence are related constructs; whereas, in the realm of conceptual change research, confidence usually refers to the misconception and belief usually refers to the new information. In this context, the more confident learners are in their misconception, the less likely they are to believe information that conflicts with it (Rich, Van loon, Dunlosky, & Zaragoza, 2016). Thus, a combination of such measures likely serves as a good proxy for commitment.

**Confidence.** Confidence in an idea should indicate, in part, commitment to that idea (Dole & Sinatra, 1998). Despite the subjective feelings of certainty that confidence instills, confidence in the accuracy of a belief is no way indicative of the actual accuracy – a phenomenon referred to as an ‘illusion of knowing’ (Koriat, 1998). These illusions of knowing may be one of the mechanisms that drives learners to feel committed to their misconceptions. Subjective confidence in the accuracy of one’s own knowledge could be generated by a number of different types of signals from memory, like how easy it is to retrieve that information, or how much information it is connected to in memory (Koriat, 2008). A misconception that is recalled often will be easy to retrieve from memory, and this ease may create an illusion of knowing.

Confidence could also be a function of actual expertise (Lodge & Kennedy, 2016) or perceived expertise (Murphy & Alexander, 2004). The more learners think they know about a topic, the more confident they will be in the accuracy of their knowledge. Research investigating the effects of perceived expertise on a number of hot topics (e.g., doctor assisted suicide) indicates a negative relationship with revision – learners are less likely to change their beliefs if

they think they know a lot about the topic (Murphy & Alexander, 2004). Within this line of reasoning, learners should be less likely to revise a misconception they are highly confident in. However, some research has indicated a somewhat surprising relationship between confidence and revision – learners are *more* likely to revise misconceptions that they are highly confident in. In these studies that indicate a *hypercorrection effect* (Butterfield & Metcalfe, 2001), after answering questions about general knowledge misconceptions and rating their confidence in the accuracy of each answer, learners were more likely to revise errors made with high confidence than errors made with low confidence (Butterfield and Metcalfe, 2001, 2006; Butterfield & Mangels, 2003; Butler, Fazio, & Marsh, 2011; Fazio & Marsh, 2009). Data supports that the occurrence of hypercorrection in these studies was due to a meta-memory mismatch; learners were surprised to find out that an answer they were highly confident in was wrong and therefore paid more attention to and had deeper encoding of the correct answer feedback for those items (Fazio & Marsh, 2011; Metcalfe, Butterfield, Habeck, & Stern, 2012).

Metcalfe and Finn (2011) provide another explanation for hypercorrection. In their study, they asked college students to answer and rate their confidence on open-ended general knowledge questions (e.g., “What is the name of the French author who wrote *The Stranger*?”). If the learners got the answer wrong, they were given a second chance to produce the correct answer either on the same open-ended question, or on multiple choice or cued recall (e.g., Albert C\_\_\_\_) versions. Learners were more likely to generate the correct answer when given a second attempt for high-confidence errors than low-confidence errors. Additionally, after hearing the correct answer, learners were more likely to claim they “knew-it-all-along” (i.e., the answer) for high-confidence errors than for low-confidence errors. This suggests that hypercorrection occurs

for high confidence errors, because the learners already had at least partial knowledge of the correct answer.

Although studies of hypercorrection purportedly have implications for conceptual change theory (e.g., Fazio & Marsh, 2009), many of the studies neglect to distinguish between incorrect answers due to a lack of knowledge (i.e., guesses) and incorrect answers due to inaccurate knowledge (i.e., misconceptions). True-false and multiple-choice question formats can inflate misconception rates on pretests by conflating misconception answers with guesses (Hughes, Lyddy, & Kaplan, 2013). To avoid this, some conceptual change researchers use very low confidence ratings to indicate guesses and remove them from analysis (Taylor & Kowalski, 2004); however that was not the case for the studies indicating hypercorrection reviewed here. True-false question formats are problematic also when used as posttests; learners can answer correctly by simply knowing what the incorrect answer is. This only measures one part of conceptual change – the outdateding of old knowledge – but not necessarily the updating of the correct knowledge. Additionally, the hypercorrection studies discussed above assessed common knowledge questions across domains (e.g., what poison did Socrates take at his execution?), so it is hard to know to what extent this information was embedded in conceptual knowledge frameworks.

Van Loon and colleagues (2015) aimed to address these concerns with question format. In their study, they measured the revision of science-based misconceptions using a combination of true-false, open-ended, and multiple-choice questions. Results indicated that a hypercorrection effect occurred for true-false posttest questions, but not for open-ended questions. When assessed with true-false questions, revision was more likely for high-confidence misconceptions than low-confidence misconceptions. However, when assessed with open-ended questions, the opposite

relationship was found – revision was more likely for low-confidence misconceptions than high-confidence misconceptions. The dual question format in this study made it possible to measure both the outdateding and updating processes of conceptual change. The true-false questions indicated that the learners were more likely to outdate misconceptions they were confident in. This finding was supported by a recent study assessing the revision of common knowledge misconceptions using true-false question formats; high confidence misconceptions were more likely than low confidence misconceptions to be outdated on a true-false question (Rich et al., 2016). However, Van Loon et al.'s (2015) study indicated that learners were more likely to update their knowledge with the correct information if they held their initial misconception in low confidence. These results demonstrate how true-false question formats may create the illusion of revision, but more importantly support the notion that high-confidence misconceptions are more resistant to revision; high confidence misconceptions discourage the adoption of new, conflicting information more so than low confidence misconceptions. While high confidence in a misconception may make learners' more resistant to adopting to-be-learned information, low plausibility and belief judgments for the to-be-learned information also indicate resistance to adopting that knowledge.

**Plausibility and belief.** Plausibility and belief are used to describe how likely and potentially truthful learners find new information to be (Chinn & Brewer, 1993; Dole & Sinatra, 1998; Kendeou & O'Brien, 2014; Lombardi, Sinatra, & Nussbaum, 2013). According to a more nuanced view, two conflicting conceptions cannot be simultaneously believable, but they can be simultaneously plausible, making plausibility more broad than believability (Lombardi et al., 2013). This aligns with a notion that a conception must be understood, then perceived as

plausible, and then believed, before change becomes likely (Posner et al., 1982; Treagust & Duit, 2003).

Plausibility, then, is an important factor affecting the likelihood of revision (Posner et al., 1982; Treagust & Duit, 2008). New information that is unbelievable or implausible is unlikely to facilitate change (Chinn & Brewer, 1993; Dole & Sinatra, 1998; Kendeou & O'Brien, 2014). Further, even if new information is considered to be plausible, it needs to be perceived as *more plausible* than the misconception for revision to be likely (Dole & Sinatra, 1998; Lombardi et al., 2013). Thus, the conceptual change process involves both the misconception becoming less plausible and less believable and the new information becoming more plausible and more believable. This process aligns with the processes of outdateding and updating, respectively.

Whether or not a learner perceives information as being plausible and believable depends on their background knowledge and any motivational factors that might encourage or discourage the incorporation of that information (Dole & Sinatra, 1998). Believability of new information is often understood in relation to the entrenchment of the misconception, which describes how deeply embedded the misconception is in other beliefs or knowledge (Chinn & Brewer, 1993). A misconception is considered to be entrenched if it provides utility for explaining a number of other beliefs or experiences. For instance, the misconception that plants get their food from the soil may be entrenched, because it explains why fertilizer is advertised as “plant food”, why plants have roots, and why plants die when they are not watered. However, a misconception may also be considered to be entrenched if it self-serves the learner by supporting one or more of the learner’s personal or social goals (Chinn & Brewer, 1993). For instance, the misconception that smoking does not cause cancer may be entrenched in the learner’s personal goal to keep smoking. Generally, the more entrenched a misconception is, the less conflicting information

will be believed, and the less likely revision will be (Chinn & Brewer, 1993). For instance, Brewer and Chinn (1991, as cited in Chinn & Brewer, 1993) demonstrated that although physics students were able to comprehend and correctly answer questions about a new physics theory they were learning, they did not report believing this new theory and subsequently did not incorporate it into their conceptual understanding. In this case, their prior conception was still perceived as more useful to them than the new physics concept.

Beyond making dissatisfaction harder to achieve, entrenched misconceptions can also cause biased evaluations of new, conflicting information, a finding known as belief bias (Evans, Barston, & Pollard, 1983) or disconfirmation bias (Lombardi et al., 2013). Belief bias causes learners to evaluate the new information in a way that will confirm their existing beliefs. To illustrate, Kunda (1990) gave students a study that reported negative health consequences associated with high caffeine intake. Students who were reportedly heavy consumers of caffeine themselves were less persuaded by the study's findings than low caffeine consumers. Importantly, the heavy consumers of caffeine also reported finding more methodological issues with the study and consequently rated it as being less valid than the low caffeine consumers – students who consumed large amounts of caffeine were more motivated to cite potential problems with the study and reject the results.

Belief bias not only serves to preserve entrenched beliefs, but is also less cognitively demanding than more sound types of reasoning, like critical evaluation (Quayle & Ball, 2000; Lombardi, Sinatra, & Nussbaum, 2013). Critical evaluation involves systematically appraising all the evidence for each conception, and then comparing those appraisals (McNeill, Lizotte, Krajcik, & Marx, 2006). Additionally, critical evaluations might also result in the learners generating metacognitive judgments about their reasoning and previous judgments (Lombardi et al.,

2013). Evaluations functioning under belief bias do not systematically evaluate the evidence for all explanations, but rather only focus on finding disconfirming evidence for the new information. Research suggests that critical evaluation is necessary for learners to change plausibility judgments in light of new evidence (Lombardi et al., 2013). However, having to simultaneously inhibit bias and systematically evaluate evidence can overwhelm learners working memory, resulting in reliance on the more automatic, less demanding, belief-biased response (Klaczynski & Gordon, 1996; Quayle & Ball, 2000). Conceptual change must be accompanied by changes in plausibility judgments (Lombardi & Sinatra, 2012). Plausibility can be increased by providing learners with instruction that promotes the critical evaluation of evidence, but will not increase as a result of normal instruction (Lombardi et al., 2013).

In sum, several conclusions can be drawn regarding the effects of expertise and commitment on conceptual change. These conclusions are certainly not without exception. Empirical conceptual change research continues to produce conflicting results due to variations in the measurement, content domain, and construct distinctions. However, it is clear that low levels of expertise and high levels of commitment to misconceptions reduced the likelihood for conceptual change. Specifically, low levels of expertise hinder learners' ability to revise, because these learners are less able to notice and resolve cognitive conflicts. When learners with low expertise are able to revise misconceptions, their conceptual change may decay and misconceptions will reemerge after instruction. Further, learners' confidence, believability judgments, and plausibility judgments, appear to have similar relationships with conceptual change; they each demonstrate the level of commitment learners have to their misconceptions, and higher levels of commitment make learners more resistant to adopting new information.

Individual factors associated with expertise and commitment provide insight into the conceptual change process, and shed light on potential obstacles to change. Importantly, the profile or concomitance of such obstacles may vary across individuals and content, or domain. For instance, one learner may not be understand why their knowledge is incorrect or different from the correct information. For another learner, the newly presented information may not be interpreted as plausible. Conceptual change is unlikely for both learners, albeit for different reasons. The required instructional response to correct misconceptions for these two learners may differ as well. The former may need to be confronted with greater cognitive conflict, perhaps by seeing more examples that do not align with his or her misconception. The latter may need assistance or a reminder to carefully and critically evaluate new information for plausibility.

### **Recommendations for Instructional Design**

Adaptive learning technology allows this level of personalized, individual instruction. Base on this review, I provide three primary recommendations for the potential design of adaptive conceptual change instruction. First, learners with low expertise need high levels of instructional support to achieve cognitive conflict during revision processes. Instructional scaffolding would need to support the detection of conflicting information by explicitly refuting the learner's misconception, identifying how it is different than the correct information, and showing the learner which information needs to change. Refutation texts do not always facilitate the detection and resolution of cognitive conflict in low-expertise learners, especially when used while learning independently in computer-based settings (Oliver, Renken, & Williams, 2017). The use of more constructive activities, like self-explaining, can help low-expertise learners confront cognitive conflicts when they have sufficient instructional support. I recommend that conceptual change instruction should adapt to low-expertise learners by presenting them with



refutation texts which directly refute their misconception and train them how to generate meaningful explanations of those refutations (McNamara, 2004). Low-expertise learners could also be supported by designing multimedia refutation texts, which have visual components like diagrams embedded within the text (Aleven & Koedinger, 2002; Kalyuga, Chandler, & Sweller, 1998; Roy & Chi, 2005). Conceptual change should adapt to higher levels of expertise by removing self-explanation training, but not self-explanations, and leaving any multimedia components unintegrated with the refutation text (Kalyuga, Chander, & Sweller, 1998; Roy & Chi, 2005).

Second, misconceptions are likely to reemerge post-instruction, particularly in learners with low levels of expertise. Misconceptions will continue to be activated in memory and learners need practice inhibiting responses to activated misconceptions. I recommend that instruction provide learners with continued retrieval practice, which includes misconception lures in questions, with feedback. This will both monitor for the reemergence of misconceptions and strengthen learners' ability to inhibit misconception responses. When misconceptions are selected in retrieval practice, which can be indicated by a learner reporting high confidence in a misconception answer, instruction should respond with refutations to remind the learner why that answer is incorrect. If misconceptions continue to be indicated, then more constructive conceptual change strategies, like the refutations with supported self-explanations described above, should be reapplied.

Third, learners with high levels of commitment to their misconception, as evidence by low belief or plausibility judgments in the new information or high confidence judgments for the misconception, should be supported with material that decreases their belief in the misconception

and increases their belief in the new information. I recommend that conceptual change instruction adapt to high levels of commitment by initially providing refutation texts which explain why the misconception is incorrect. These refutations can further support learners with different levels of expertise by considering my first recommendation. The presentation of refutation texts should subsequently be followed by guided critical evaluation exercises, which prompt learners to weigh all of the evidence for the misconception and correct information, perhaps through self-explaining. These critical evaluation activities should be highly supported, considering that critical evaluation is a cognitively demanding process for learners with high levels of commitment to their misconception.

The next step towards adaptive conceptual change instruction is to begin implementing modules that measure the revision of misconceptions and collect data on relevant individual differences, like expertise and commitment, in large scale educational contexts like Massive Online Open Courses (MOOCs). Conceptual change instruction is particularly necessary in domains which are often highly misconceived, like physics and biology. Implementing modules that measure and facilitate conceptual change in MOOCs, perhaps using the recommendations above, will provide data that empirically model individual differences in the conceptual change process. In turn, this data will support further iterations of conceptual change instruction and provide insight into conceptual change theory.

In conclusion, conceptual change is a particularly complex type of learning that can benefit from learner-level adaptations to instruction. The findings from this paper clearly indicate that learners' prior knowledge level, and their commitment to that prior knowledge, have significant effects on conceptual change outcomes. The moderating effects of these learner-level characteristics, in addition to other factors which may be relevant to conceptual change

processes, like learners' epistemology or reasoning ability, provide valuable opportunities to optimize conceptual change instruction across learners. This opportunity is just beginning to be realized, and the implementation of conceptual change models in MOOC environments is the next step to bridging conceptual change and adaptive educational technologies.

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**INVESTIGATING INDIVIDUAL DIFFERENCES IN THE CONCEPTUAL  
CHANGE OF BIOLOGY MISCONCEPTIONS USING COMPUTER-BASED  
EXPLANATION ACTIVITIES**

*“One can expect interactions between learner characteristics and instructional method. Where these exist, the instructional strategy that is best for the mean is not best for all persons.”*

*-Cronbach and Snow, 1977, p1.*

Understanding how instructional tasks affect learning across students has been a priority for educational psychologists for over 40 years. While early educational psychology research began to empirically identify aptitude-treatment interactions (e.g., Cronbach & Snow, 1977), or moderating effects of prior knowledge on instructional tasks’ effectiveness, results from studies were hard to replicate, and little was known about the underlying cognitive mechanisms behind the interactions (Kalyuga & Renkl, 2010). Since then, the development of cognitive load theory – a framework used to explain aptitude-treatment interactions (Chandler & Sweller, 1991) – as well as the refinement of the statistical analyses used in educational settings (Ackerman, Sternberg, and Glaser, 1989), have led us to a more thorough understanding of how and why instructional tasks affect individual learners differently. Research in this field continues to evolve alongside technology and has resulted in the realization of learner-tailored instruction using adaptive courseware (De Jong, 2010; Kalyuga, 2013; Olney, Brawner, Pavlik & Koedinger, 2015); computer-based instruction can now adapt to learner characteristics to maximize learning across individuals. However, this movement is still in its infancy, with most adaptive courseware still in experimental stages (Pugliese, 2016. SRI, 2016).

Interactions between learner characteristics and instructional tasks are often constrained to the learning domain they are identified in, because learning across domains may have different objectives. Learning in science domains is of particular interest to educational psychology. National initiatives focus on increasing the number of students and proficient teachers teaching STEM classes in K-12 settings (National Math and Science Initiative, 2010). Science domains are also interesting given the complex nature of learning in a domain in which students come into the classroom with relevant misconceptions (Carey, 1985; Chinn & Brewer, 1993; Wandersee, Mintzes & Novak, 1994; Wellman & Gelman, 1992). Learning scientific concepts goes far beyond the memorization of declarative knowledge and involves a number of complex component processes, like the consolidation of new and prior knowledge, the evaluation of multiple sources, and the evidence-based generation of inferences and explanations (Chi, 2005; Zimmerman, 2007). The design of instructional methods in science focuses on facilitating these complex processes. In particular, a great deal of the research on learning in science domains focuses on facilitating conceptual change, because misconceptions in this domain are particularly common and resistant to normal instruction (Chi, 2005; Chinn & Brewer, 1993; Tippet, 2010).

Conceptual change instruction, which facilitates knowledge revision, and conceptual change research primarily employ refutation texts (Tippet, 2010), with other more student-centered approaches like self-explaining (Chi, 2009) receiving much less empirical attention. In addition, it is unknown what types of demands knowledge revision tasks place on working memory and how those demands might vary as a function of their prior knowledge level. Answering these questions is crucial to the development of adaptive science instruction. To understand the role of prior knowledge levels within different knowledge revision tasks, the current study investigated the effects of refutations, in the form of correct answer feedback,

followed by either self-explanations or instructional explanations. Assessing the effectiveness of explanation tasks on revision, and identifying any interactions with prior knowledge, will have significant implications for the design of potentially adaptive conceptual change instruction.

In order to establish a framework for interpreting the study presented here, I first discuss Cognitive Load Theory – which is used to explain interactions between learner characteristics and instruction. Second, I detail the process of conceptual change and outline the specific photosynthesis misconceptions addressed in this study. Third, I review prior work regarding self-explanation and instructional explanation tasks before introducing the present research.

### **Cognitive Load Theory**

Cognitive load theory (CLT) is a framework designed to identify interactions between learner characteristics and instructional task demands and determine which interactions lead to cognitive overload in learners (Chandler & Sweller, 1991; Sweller 1988). In turn, findings from CLT research are used to provide recommendations for instructional design. Specifically, CLT considers interactions between three primary cognitive processing components, including a limited working memory capacity, unlimited long term memory, and the encoding of new information (Sweller, van Merriënbroer, & Paas, 1998; Sweller, 1999). The idea of a limited working memory capacity was proposed long before CLT by Miller (1956), who found the most information people can keep in mind at one time is  $7 \pm 2$  items. Although this finding is still used as a benchmark today, the more recent suggestion according to CLT is that working memory can only simultaneously operate on about half of those items (Cowan, 2001), and only for few seconds, with most items being lost after 20 seconds without rehearsal (van Merriënbroer & Sweller, 2005). However, these constraints do not apply to information that is brought in from long term memory (instead of novel information; Ericsson & Kintsch, 1995).



The idea of an unlimited long term memory suggests that a learner can access an unconstrained amount of information from long term memory without placing a burden on working memory capacity. In other words, learners can utilize their prior knowledge at little to no expense. Prior knowledge helps support the processing of new information (Kalyuga & Sweller, 2005) – the third component considered in CLT. The processing of new information is a primary mechanism of learning, and CLT describes how the processing of new information depends on the learner's prior knowledge level. The more prior knowledge a learner has, the more supported learning will be. It follows that the more supported learning is, the less demanding that learning is on working memory, and the less likely working memory is to be overloaded. CLT theory is utilized to investigate the demands that instructional tasks place on working memory capacity, how those demands vary as a function of prior knowledge levels, and which interactions lead to the greatest learning gains (Plass, Moreno & Brunken, 2010).

CLT outlines three different types of demands, otherwise known as loads, that an instructional task can place on working memory: intrinsic, extraneous, and germane (Chandler & Sweller, 1991). Intrinsic cognitive load is a productive type of processing which involves the incorporation of new information with prior knowledge (Kalyuga, 2007). Intrinsic load is inherent to the material being learning in the task, because it is determined by the complexity of the information (van Merriënbroer & Sweller, 2005). More specifically, intrinsic cognitive load is determined by the element interactivity of the to-be-learned material (Sweller, 2010). Element interactivity describes the number of elements that need to be simultaneously processed in working memory in order to learn the material. To-be-learned material, which is high in element interactivity, is more complex and has more pieces of information that need to be processed. For example, when learning to read (a process high in element interactivity), each letter within a

word, as well as their corresponding sounds, must be understood separately before the word as a whole can be decoded (Sweller, 2010).

Element interactivity, and the resulting intrinsic load, are further determined by prior knowledge levels. Prior knowledge is used to chunk multiple elements together into a single element, thereby reducing the number of elements needing to be processed. Using the example from before, a more advanced reader has sufficient prior knowledge to chunk letters into words, and thus does not have to process each letter separately in order to decode a word – only reading novices have to sound words out to comprehend them. While elements are at the word level for a reading expert, they are at the letter level for a reading novice. Thus, prior knowledge will determine how much a learner can process at one time, thereby making the intrinsic load of a to-be-learned material variable across learners of different expertise. Because intrinsic cognitive load is a combination of inherent characteristics of the learner and to-be-learned material, it cannot be altered by task design features (Kalyuga, 2007). Rather, tasks should be designed around the intrinsic load. This can be accomplished by managing the complexity of material using design features like sequencing or segmenting elements (Sweller, 2008) and managing the prior knowledge level by varying levels of support.

Extraneous cognitive load is also determined in part by material complexity and prior knowledge levels, but unlike intrinsic load, it is considered to be a wasteful type of cognitive processing that results from the design of the instructional task itself (Kalyuga, 2007).

Extraneous cognitive load occurs when the intrinsic load is not managed properly by the task or the task has distracting design features. Simply put, anything that poses an extraneous load distracts the learner from learning through the task, because it devotes limited cognitive resources to irrelevant processing (van Merriënbroer & Sweller, 2005). Poor design features like

insufficient instructional support, poor presentation design, or inappropriate task sequence can distract from necessary learning processes (Kalyuga, 2007). For instance, consider a textbook passage that includes a number of words the learner does not understand; that learner will need to leave the task to look up definitions before continuing. Or, consider a computer-based activity, where the learner has to participate in a great deal of unnecessary scrolling and website navigation to complete the task. These unnecessary activities can negatively impact learning by taking up processing capacity in an already constrained working memory. While intrinsic load itself cannot be altered by design, extraneous load can. To produce an optimized learning opportunity, instructional tasks should be designed around material complexity and the learner's prior knowledge to manage intrinsic load and minimize extraneous load (Kalyuga, 2015; Mayer & Moreno, 2003).

Germane cognitive load differs from intrinsic and extraneous load (Kalyuga, 2007); it refers to the amount of working memory resources that are directed to learning strategies, like asking relevant questions or generating an explanation (Sweller et al., 1998). If extraneous load is low, and the intrinsic load is managed, then instruction can direct leftover processing power to strategies that encourage learning (Chandler & Sweller, 1991). However, if extraneous load is high, there may not be enough working memory resources left to devote to germane processing (Kalyuga, 2007). Cognitive load theory recommends that extraneous load be minimized so that germane processing of the intrinsic load can be maximized. However, processing that is germane for one learner may be extraneous for another. Tasks that aim to enhance germane cognitive load may overwhelm novice learners' working memory (Sweller, 2008). Identifying the interactions that determine what is extraneous for a learner is thus a key part of designing appropriate instruction.

**The moderating effects of prior knowledge.** Interactions between learners' prior knowledge levels and the effects of instruction are ubiquitous in education, and the nature of these interactions depends on the instructional task being used. The optimal amount of instructional support varies according to learners' expertise level (Sweller, Ayres, Kalyuga, & Chandler, 2003). Oftentimes, tasks that apply a consistent amount of instructional support across all learners only facilitate learning in individuals at a certain prior knowledge level – maximizing learning for individuals at one level of expertise but hindering learning for individuals at a different level (Kalyuga et al., 2003). These interactions occur under two scenarios: 1) when an instructional task does not provide enough external guidance for a learner with low levels of prior knowledge, and 2) when an instructional task provides unnecessary external guidance to a learner with high levels prior knowledge (Kalyuga, 2007). In the former scenario, learners must employ search processes to find the information necessary to engage in the task. In the latter scenario, learners must reconcile redundant information in order to engage in the task; a prior knowledge interaction in this scenario is more specifically known as an expertise reversal effect (Sweller, 2008). In both scenarios, an extraneous load, caused by an inappropriate level of instructional support, is placed on one group of learners but not the other.

Interactions between prior knowledge levels and instruction occur across a number of different domains, tasks, and populations (for review, see Kalyuga, 2007), resulting in specific implications and recommendations for instruction (Kalyuga, 2015; Sweller, 2008). These recommendations are based on the documented effects of particular tasks on cognitive load across learners. For instance, redundancy effects are expertise reversal effects which occur when high prior knowledge learners are cognitively overloaded by sifting through information that they already know. In addition to avoiding redundancy effects, CLT recommends that

instructional design should consider goal free effects (i.e., novices learn better from kinematics problems when instructions are not specific), worked example effects (i.e., novices learn better from studying already-solved problems than trying to solve them themselves), and imagination effects (i.e., experts, but not novices, can learn effectively from imagining problem solving; Sweller, 2008). Such effects are clear in knowledge building tasks (Kalyuga, 2007), but it remains unclear how instruction should be adapted to best support knowledge revision.

### **Conceptual Change**

Learning is most often associated with knowledge building, in which new information is added to existing knowledge. However, a different type of learning deals with knowledge revision, more commonly referred to as conceptual change. Conceptual change is the process of correcting erroneous knowledge and replacing it with correct knowledge (Chi, 2008) and is necessary when students hold misconceptions. Simply defined, misconceptions are instances of inaccurate prior knowledge that conflict with the knowledge currently accepted by experts (Tippet, 2010). Misconceptions are common, especially in domains like science, where students enter classrooms with their own personal theories to explain phenomena (Chi, 2005; Chinn & Brewer, 1993; Guzzetti, 2000). Students must revise their existing misconceptions, or they may hinder further learning (Alvermann & Hague, 1989; Dole, 2000; Guzzetti et al., 1993; Pintrich, Marx, & Boyle, 1993; Sinatra & Pintrich, 2003).

Misconceptions exist at various grain sizes. Some misconceptions may be contained to a single erroneous fact, while other misconceptions may span across several concepts and represent fundamental errors in reasoning. Chi (2008, 2013) describes three levels, or grain sizes, of misconceptions. Misconceptions at the first level are referred to as false beliefs. These misconceptions are narrow in scope and are indicated when a learner's incorrect knowledge is

contained to a single fact. For instance, a learner may have the false belief that *bats are blind*. Misconceptions at the second level are referred to as flawed mental models. These misconceptions have broader scopes and are indicated when a learner has multiple, non-conflicting, false beliefs regarding the same concept. For instance, a learner may have a flawed mental model of the concept of seasonal change, because the learner incorrectly believes that the earth is further from the sun during the winter, the earth's tilt is unrelated to seasonal temperature, and seasons are caused by the earth's proximity to the sun. Misconceptions at the third level, the largest grain size, are referred to as category mistakes. Category mistakes are indicated when the learner incorrectly understands how members of a certain category function and are indicated when a learner mis-categorizes a new object or phenomenon. For instance, a learner may misunderstand a number of concepts related to motion, because they misunderstand the overarching concept of force as being an entity instead of a process (Chi, 2013). Across all these types of misconceptions, the level can indicate how much revision needs to occur. While a false belief only requires the revision of one statement, correcting flawed mental models requires the combination of multiple false belief revisions, and correcting category mistakes is a more complex revision process that includes assigning knowledge to a different category (Chi, 2008). Thus, conceptual change may be more difficult to achieve in some situations than others.

While encountering information that conflicts with prior knowledge is considered to be a fundamental aspect of learning science (Chinn & Brewer, 1993), it is notoriously difficult to get learners to revise their misconceptions and achieve conceptual change (Chi, 2005). Instruction specifically designed to guide learners to revision is often necessary to facilitate conceptual change in students, and, even then, conceptual change does not always occur (Guzzetti, 2000; Tippet, 2010). Research suggests that conceptual change is only likely to occur if instruction

facilitates the dual activation of the misconception and correct information in working memory, and the learner then mentally experiences a conflict between the two (van den Broek & Kendeou, 2008). This co-activation and cognitive conflict are crucial for change (van den Broek & Kendeou, 2008), because learners are not likely to revise misconceptions unless they are aware the misconceptions exist (Chi, 2005).

Even if learners are aware of their misconception, they may decide not to revise it. Instead, they may opt to ignore the conflicting information, or simply memorize the new information without replacing the misconception (Posner, Strike, Hewson & Gertzog, 1982). Further, a learner may reason that the new information is incorrect and reject it, reason that the new information is irrelevant and reject it, decide to deal with the conflicting information later, or reinterpret the new information so that it no longer conflicts with their misconception (Chinn & Brewer, 1993).

A number of individual differences may make a learner less likely to revise. For instance, learners with low prior knowledge may be unable to notice a conflict between their misconception and the new information and therefore not realize the need to change (Dunbar, 1995; Limon & Carretero, 1997; Linnenbrink-Garcia Et Al, 2012; Braash, Goldman, & Wiley, 2013; Schauble, Glaser, Ragavan & Reiner, 1991). Research suggests a sufficient level of domain knowledge is requisite to compare and evaluate information (Limon, 2003). Conversely, a learner with high prior knowledge may use their expertise to discredit and reject, or reinterpret, the new information (Chinn & Brewer, 1993; Crocker, Fiske, & Taylor, 1984; Dole & Sinatra, 1998; Thargard, 1992; Vosniadou, 1994). The present study aimed to identify revision tasks that would promote conceptual change in a relatively novice group of learners who were enrolled in introductory biology courses. Learners in this population typically have a number of

misconceptions concerning photosynthesis and respiration.

**Photosynthesis misconceptions.** The abstract concepts associated with photosynthesis and respiration are some of the hardest for students of all ages to correctly understand (Bahar, Johnstone, & Hansell, 1999), and this understanding is key for students to grasp not only plant nutrition but ecology in general (Esiobu & Soyibo, 1995; Anderson, Sheldon, & DuBay, 1990). Students come into classrooms with intuitive, but inaccurate, pre-instructional understandings of how plants get energy for growth, and those misconceptions persist through instruction (Anderson, Shelton, & Dubay, 1990). Photosynthesis misconceptions are found in elementary school (Roth, 1990), middle school (Svandova, 2014; Yenilmez & Tekkaya, 2006) high school (Tas, Cepni, & Kaya, 2012) college students (Anderson, Shelton, & Dubay, 1990; Prossner, 1994; Södervik, Virtanen, & Mikkilä-Erdmann, 2015), and pre-service science teachers (Galvin, Simmie, & O'Grady, 2015).

Biologists understand photosynthesis and respiration as chemical processes of energy conversion. Photosynthesis uses light energy to synthesize inorganic sources (i.e., CO<sub>2</sub> from the air) into chemical potential energy and oxygen. In turn, respiration uses the potential energy and oxygen produced during photosynthesis to produce usable energy (i.e., ATP; Anderson, Shelton, & Dubay, 1990). In the most simplified terms, plants make sugars using photosynthesis and respiration turns those sugars into food the plant can use. The commonly indicated misconceptions pertaining to photosynthesis and respiration (discussed below) represent flawed mental models; while students are able to understand basic propositional statements about the concepts (e.g., photosynthesis takes part in the green parts of plants; Maramaroti & Galanopoulou, 2006) and the general category of the concepts (i.e., that they are both *processes*), they hold multiple false beliefs regarding these processes that result in consistently inaccurate



predictions.

Students falsely believe that respiration only takes place when photosynthesis is not (Svandova, 2014), that plants get energy for growth from the ground through their roots (AAAS, 2016; Galvin et al., 2015), that respiration in plants is the same as breathing in animals (Galvin et al., 2015), that plants can stay alive without respiration (Svandova, 2014), that photosynthesis and respiration are the same thing (Svandova, 2014), or even that plants do not respire (Amir & Tamir, 1994). These misconceptions indicate that students misunderstand the function of these processes and how they work together (Anderson, Sheldon, & Dubay, 1990; Svandova, 2014). Students may memorize specific knowledge statements pertaining to photosynthesis and respiration during instruction, but they do not sufficiently incorporate this knowledge into their conceptual understanding (Tas, Cepni, & Kaya, 2012).

Traditional general biology instruction may not be sufficient to revise these misconceptions. Even after taking college-level biology courses, undergraduate students still indicate high levels of misconceptions (Anderson, Shelton, & Dubay, 1990). Beyond normal instruction, research indicates that specially designed instructional texts can increase correct understanding of photosynthesis and respiration (Balci, Cakiroglu, & Tekkaya, 2006; Södervik, Virtanen, & Mikkilä-Erdmann, 2015). Less traditional revision tasks like computer-assisted concept mapping tasks (Tas & Cepni, 2012), computer-assisted instructional modules (CAIM) that focus on problem solving (Tas, Cepni, & Kaya, 2006), and even concept cartoons (Ekici, Ekici, & Aydin, 2007) may also improve conceptual understanding of photosynthesis and respiration. The current study aimed to assess the effects of two different computer-assisted explanation tasks, self-explanations and instructional explanations, on the revision of misconceptions pertaining to photosynthesis and respiration.

## Explanation Tasks

**Self-explaining.** Learning is often enhanced by prompting students to generate explanations about the content, a finding known as the *self-explanation effect* (Fonseca & Chi, 2011; VanLehn & Hausmann, 2007). Self-explaining actively engages students in constructing knowledge and encourages them to monitor their own learning (Roy & Chi, 2005) Research assessing knowledge building indicates positive effects of self-explanation tasks on learning across both problem-solving and more declarative-based learning from texts (Dunlowsky, Rawson, Marsh, Nathan & Willingham, 2013). Self-explanation tasks are used in a variety of ways. In some cases, learners are instructed to read an instructional text and stop to explain each line of the text to themselves (Chi, 1996; Chi, Deleeuw, Chiu, & Lavancher, 1994). In other cases, learners are asked to explain each step while solving a problem (e.g., Alevan & Koedinger, 2002; Chi, Bassok, Lewis, & Reimann, 1989), to explain a worked example (e.g., Hausmann & VanLehn, 2007), or to explain category membership (Williams, Lombrozo, & Rehder, 2013; Williams & Lombrozo, 2010) among other self-explanation tasks (see Rittle-Johnson & Loehr, 2016 for a recent review). Self-explaining encourages learners to incorporate both the knowledge being learned and their prior knowledge into their explanation and produce inferences that fill any gaps in knowledge (Chi, 1996; Fonseca & Chi, 2010).

Self-explaining enhances knowledge building in most contexts, and may also aid conceptual change. Theoretically, self-explaining should prompt misconception revision by highlighting inconsistencies in knowledge, promoting cognitive conflict, and facilitating the reconstruction of a correct knowledge structure (Chi, 2008). However, empirical research has thus far only demonstrated positive effects of self-explanations on the revision of misconceptions in statistics (Williams, Lombrozo, Hsu, Huber, & Kim, 2016). Despite a general call for research

directly comparing the effects of self-explanations and other instructional tasks (Rittle-Johnson & Loegr, 2016), no research compares its utility for revision.

Self-explaining may aid conceptual change, but as a knowledge building task, it is prone to interactions with prior knowledge. Learners with higher prior knowledge are able to generate better explanations than low prior knowledge learners, and better-quality explanations result in more learning (Roy & Chi, 2005). Comparisons of self-explanations to other strategies indicate the effect of prior knowledge is further explained by its effects on cognitive load. In one such study, Leppink, Broers, Imbos, van der Vleuten and Berger (2012) had students read statistics texts and then asked students to either answer questions about the text, answer questions and provide explanations, or study worked examples. While high prior knowledge learners benefited most from answering questions and providing explanations, low prior knowledge learners benefited most from studying worked examples; answering questions and providing explanations overloaded working memory in low prior knowledge learners (Leppink et al., 2012). Such findings fall in line with *worked example effects*, which occur when novices benefit from studying worked examples, while more expert learners benefit more from less supportive tasks, like problem solving or self-explaining (Ayres & Paas, 2012).

**Instructional explanations.** Instructional explanations direct readers' attention to and elaborate on pertinent information (Wittwer & Renkl, 2008). Typically, they are explanations generated by domain experts and can be used to explain a new concept and develop background knowledge, or in later phases of learning to elaborate on a concept and restructure knowledge if necessary (Wittwer & Renkl, 2008). The quality of instructional explanations, and their subsequent effects on learning, can vary widely (Roelle, Muller, Roelle & Berthold, 2015), and their effects are consistently prone to expertise reversal (Rey & Fischer, 2013; Paas & Van Gog,

2006; Wittwer & Renkl, 2010). Instructional explanations typically only benefit low expertise learners whose prior knowledge is insufficient for less supported tasks like problem solving or self-explaining. In high prior knowledge learners, instructional explanations present information that is already known, eliciting redundancy effects (Sweller, 2008) and hindering further learning.

When used to promote conceptual change, instructional explanations are adapted to address and refute misconceptions. These *refutation texts* include three primary components: the statement of the misconception, the refutation of that misconception – in which the inaccuracy of the misconception is pointed out – and an explanation of the correct scientific understanding (Guzzetti, 2000). Refutation texts are designed to promote cognitive conflict in learners and are an effective way of promoting the revision of misconceptions at the false belief and flawed mental model levels (Chi, 2008; Guzzetti, 2000), including the revision of photosynthesis and respiration misconceptions (Balci, Cakiroglu, & Tekkaya, 2006; Södervik, Virtanen, & Mikkilä-Erdmann, 2015; Tippet, 2010). However, the exact effects of prior knowledge on conceptual change using refutation texts are unclear. Some studies indicate that refutation texts are more effective for facilitating change in low prior knowledge learners than high prior knowledge learners (Cordova, Sinatra, Jones, Taabsoobshirazi, & Lombardi, 2014; Södervik, Virtanen, & Mikkilä-Erdmann, 2015). Other research suggests that students with low prior knowledge levels will not be able to learn from refutation texts unless they are supported by additional instruction (Guzzetti, 2000).

In sum, self-explaining and reading instructional explanations are both beneficial to learning, but which instructional task is *most* effective will depend on the prior knowledge level of the learner. When used for knowledge building, self-explanations benefit high knowledge

learners and instructional explanations benefit low knowledge learners. However, it is unclear if these same prior knowledge interactions also occur when the tasks are used for conceptual change. Since prior knowledge is changing during revision, more or less prior knowledge may not affect cognitive load in the same way. If the same types of prior knowledge interactions occur during conceptual change, then cognitive load theory may also be applicable and useful for understanding the effects of revision tasks, and there may be valuable opportunities to optimize conceptual change learning by adapting the revision task to learners' knowledge levels.

### **The Present Research**

The present study investigates the effects of two revision tasks, instructional explanations and self-explanations, on the revision of photosynthesis misconceptions in undergraduate biology students with a primary aim of identifying any interactions between learners' prior knowledge and the revision tasks. I address several research questions with this study. First, how do self-explanation prompts and instructional explanations affect students' revision of misconceptions when compared to no explanations (Research Question 1)? I hypothesized that self-explanation prompts would be more effective at facilitating revision than instructional explanations. Second, do the effects of self-explanations or instructional explanations vary as a function of learners' prior knowledge levels (Research Question 2)? In line with previous findings on knowledge building, I hypothesized that self-explanations would benefit high prior knowledge learners more than low prior knowledge learners, and instructional explanations would benefit low prior knowledge learners more than high prior knowledge learners. Third, how do cognitive load scores affect learning in each condition (Research Question 3)? I hypothesized that increases in cognitive load scores would predict decreases in learning for all conditions. Fourth, how does cognitive load during each revision tasks relate to prior knowledge

(Research Question 4)? I hypothesized that cognitive load would have a negative correlation with prior knowledge during self-explanations and a positive correlation with prior knowledge in the instructional explanation condition.

## Method

### Participants

Five-hundred and seventy four undergraduate students from Georgia State University volunteered to participate in this study. Participants were recruited from Introductory Biology II courses for majors (i.e., BIO 2108) and non-majors (i.e., BIO 1104). All participants had previously passed an Introductory Biology I course. Students received course credit for completing each photosynthesis activity, but those who opted to participate in this study did not receive any additional compensation.

Of the 540 participants initially recruited, 125 did not complete the posttest and were excluded from analysis. Additionally, 12 participants started but did not complete the activities during the first session and were also excluded from analysis. This level of attrition was expected for a computer-based activity that involved two time points, and a large sample size was recruited in anticipation of this. The 403 participants recruited at the beginning of the study were randomly assigned to either a self-explanation condition ( $n = 118$ ), instructional explanation condition ( $n = 140$ ), or no explanation condition ( $n = 145$ ) at the beginning of the first session. The final sample size amounted to 403 participants.

The final sample of 403 participants consisted of 85 biology majors and 318 non-majors. For the participants who reported demographic information, 71% were female, 28% were male, and 1% preferred not to answer. Additionally, 39% reported being African American, 28% reported being Caucasian, 13% Asian/Pacific Islander, 8% Hispanic, 8% other/multiracial, and

4% preferred not to answer.

Thirty-four participants volunteered to participate during the second session of the study and only participated in the posttest. This incidental posttest-only group served as baseline to compare the effects of the three activity conditions to but are not part of the final sample size ( $N = 403$ ) used to address the research questions.

### **Materials and Procedure**

Research was conducted through Qualtrics Online Survey Software. Participants completed two separate online sessions. The first session, which included a prior knowledge assessment and activity, took approximately 35 minutes. The second session, which included a posttest, took approximately 20 minutes. The sessions were both assigned as at-home review activities at the beginning of the semester. Participants completed sessions from computers, either in class or at home. To implement a one-week delay between the first and second session, instructors provided the links to the sessions one week apart. Additionally, Qualtrics Survey Software sent participants reminder e-mails with the link to the second session exactly one week after they completed the first activity.

**Session 1.** Participants completed informed consent and were then directed to a prior knowledge assessment. Before starting the assessment, participants received the following instructions: “We are interested in how much you already know about photosynthesis. In the following section, you will answer 15 multiple-choice questions. Please answer all the questions to the best of your ability. You are not being graded on accuracy, so please do not look up the answers. If you do not know an answer, try to select the best option you can.”

*Prior knowledge assessment.* A 15-item assessment was used to measure participants’ topic-specific knowledge of photosynthesis. All 15 items were multiple-choice questions

acquired from the test bank of the *Capturing Solar Energy: Photosynthesis* chapter of an introductory biology textbook (Audesirk, Audesirk, & Byers, 2013). Biology instructors were asked to select questions that were covered in the Introductory Biology I course and ranged in difficulty. See *Appendix A* for questions from the prior knowledge assessment.

After completing the prior knowledge assessment, participants were randomly assigned to 1 of 3 instruction conditions: self-explanation, instructional explanation, or no explanation. The activity guided participants through 12 activity questions, associated measures, and any assigned explanation prompt.

*Revision Activity Questions.* Twelve activity questions were included in the revision activity and were adapted from previous measures of photosynthesis and respiration misconceptions (AAAS 2061, 2016; Amir & Tamir, 1994; Boomer & Latham, 2011; Galvin, Moonie, Simmie, & O'Grady, 2015; Haslam & Treagust, 1987). The activity questions targeted common misconceptions regarding photosynthesis and respiration by including those misconceptions in the answer choice options. During the design of this study, biology instructors working with this population expressed that many students held misconceptions regarding the relationship between photosynthesis and respiration. The information obtained from instructors was consistent with common photosynthesis and respiration misconceptions found in the literature, which are described below.

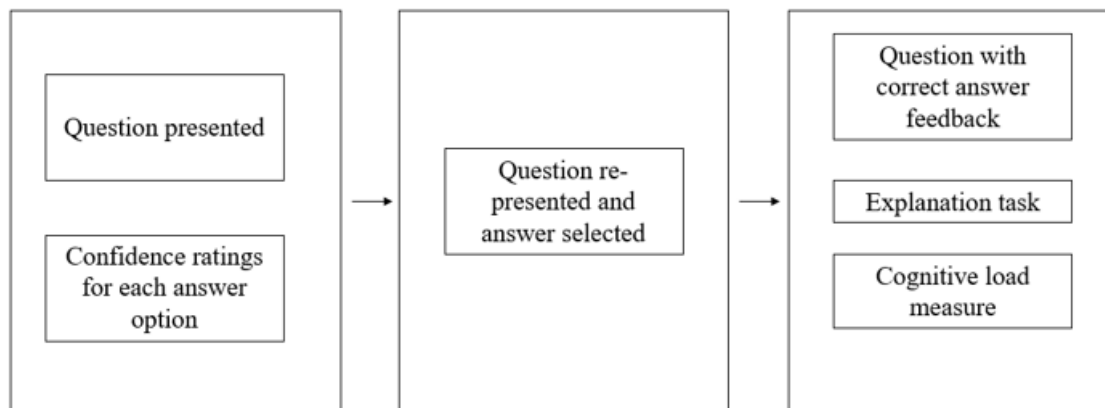
The following general misconceptions were expressed, in a variety of ways, as answer options throughout the revision activity questions: plants get their food from the soil (AAAS 2016, 2016; Galvin et al., 2015; Svandova, 2014), plants do not respire (Amir & Tamir, 1994), plants only respire when they are not photosynthesizing (Haslam & Treagust, 1987; Galvin et al., 2015; Svandova, 2014), and respiration in plants is synonymous with breathing in animals



(Anderson et al., 1986; Galvin et al., 2015). Misconceptions were embedded as answer choices in multiple questions throughout the activity in order to provide multiple opportunities for a misconception to be activated and potentially revised. Misconceptions are often activated by some questions but not others (Eylon, Ben-Zvi, & Silberstein, 1987). The revision activity included both knowledge and application questions. Knowledge questions prompted participants to correctly identify facts or basic concepts (e.g., which of the following about respiration is true?), and application questions prompted participants to apply their knowledge to a scenario (e.g., in the experiment depicted above, what happened to the mass lost in the ‘water, no light’ treatment?). Each multiple-choice question had 4 to 5 answer choices and at least one misconception embedded in an answer choice. Some questions had more than one misconception answer choice. See *Appendix B* for activity questions.

*Confidence ratings.* After initially reading a question, participants were prompted to report how confident they were in the accuracy of *each* answer option. A 5-point Likert scale was used to measure participants’ confidence in the accuracy of each answer choice for activity and posttest questions. Instructions prompted participants to *please indicate how confident you are in the accuracy of each answer choice*, with *1* indicating *absolutely confident it’s wrong* and *5* indicating *absolutely confident it’s right*.

*Explanation tasks.* After rating their confidence in each answer choice, participants were presented with the question again and asked to select the best answer. On the following page, the question was presented with correct answer feedback (i.e., correct answer highlighted and pointed out in the question). Directly below the correct answer feedback, any relevant explanation prompts were presented, followed by a cognitive load measure. See *Figure 1* for a visual depiction of an activity question.



*Figure 1.* The procedure for each activity question. The procedure continued like this for all 12 activity questions

For the self-explanation condition, participants were prompted to “in 3-5 sentences, please explain why X is the correct answer to the question” and subsequently entered their explanation into a text box. Participants in the instructional explanation condition were prompted to carefully read an instructional explanation, which was provided below the correct answer feedback.

For the instructional explanation condition, twelve paragraph-long explanations (~4 sentences) of the correct answer to each activity question were written by biology instructors. The explanations explained the correct answer to each question and either indirectly refuted or directly refuted relevant misconceptions contained in the question. For example, in a question including the misconception *respiration only takes place when photosynthesis is not* in an answer choice, the instructional explanation for that question indirectly refuted the misconception (i.e., “respiration is taking place in plants at all times...”). In a different question including the misconception *plants get food from the ground* in an answer choice, the instructional explanation directly refuted that misconception (i.e., “Plants do not ‘get food’ from anywhere. Plants make their own food...”). Because some of the activity questions had more than one misconception embedded as answer options, directly refuting a specific misconception in those explanations

was not appropriate. However, both direct and indirect refutations can be effective (Chi, 2013). See *Appendix C* for instructional explanations for each question. Participants in the No Explanation condition were only provided with the correct answer feedback and did not receive any explanation prompts.

*Cognitive Load Measure.* Following their assigned explanation prompts (or lack thereof), all participants completed a cognitive load measure. A 7-point Likert scale was used to measure cognitive load in participants. The scale was adapted from a cognitive load measure validated by Paas (1992), with a reported reliability coefficient ( $\alpha$ ) of .90. The scale in this study asked participants to self-report *how hard* it was to complete the activity, with 1 indicating *not difficult at all* and 7 indicating *very, very difficult*. More specifically, participants in the self-explanation condition were prompted to report *how hard was it to generate your explanation*, participants in the instructional explanation were prompted to report *how hard was it to understand the explanation above*, and participants in the no explanation condition were prompted to report *how hard was it to understand the correct answer*.

After completing the cognitive load measure, participants were directed to the next activity question. The procedure continued like this for all 12 activity questions. The order of the 12 activity questions was randomized across participants. After completing the activity, participants were asked to provide their student ID, instructor, course number, and email address.

**Session 2.** The following week, instructors and Qualtrics Survey Software both provided participants with the link to the second session. At the beginning of the second session, participants were asked whether they completed the first session. Participants that indicated they had not completed the first session were directed to the informed consent form before being routed to the posttest (i.e., posttest-only group participants). Participants who indicated that they

completed the first session were routed directly to the posttest.

*Posttest.* A 24-item multiple-choice posttest was used to measure learning. The posttest included the 12 original activity questions and 12 new near-transfer questions. Near-transfer knowledge questions addressed the same content as knowledge activity questions and maintained the same structure as activity application questions. See *Appendix D* for posttest questions. Before selecting their answer to a question, participants were prompted to rate their confidence in the accuracy of each answer choice before selecting their answer. After answering all 24 posttest questions, participants answered demographic questions and again provided their student ID, course, and instructor, after which they were debriefed.

## Results

In order to provide context for my analyses, I first describe the reliability and descriptive statistics for performance on the prior knowledge assessment, revision activity, cognitive load measure, and posttest before addressing research questions.

### Descriptive Statistical Analyses

**Prior knowledge assessment.** Overall, the prior knowledge assessment indicated that participants had low topic knowledge of photosynthesis. The average prior knowledge assessment score was 4.62 ( $SD = 2.23$ ) items correct out of 15. Majors ( $M = 5.00$ ;  $SD = 2.44$ ) and non-majors ( $M = 4.55$ ,  $SD = 2.16$ ) did not have significantly different prior knowledge scores,  $F(1, 401) = 2.43$ ,  $p = 0.12$ . However, male participants ( $M = 5.28$ ,  $SD = 2.61$ ) had significantly higher prior knowledge scores than female participants ( $M = 4.22$ ;  $SD = 1.90$ ),  $F(2, 297) = 7.81$ ,  $p < .001$ . Prior knowledge scores were not significantly different across the three conditions ( $p = .90$ ).

Reliability estimates for the prior knowledge assessment were surprisingly low ( $\alpha = .42$ ).

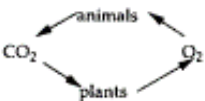
Low reliability may be expected if students do not have measurable levels of that knowledge – reliability would be expected to be 0 if students had no knowledge of the content and were guessing (Carver, 1974). A consequence of the low reliability in the prior knowledge assessment could be underestimated effects of that knowledge (Dochy, Segers, & Buehl, 1999). However, prior knowledge scores were significantly correlated with revision activity scores ( $r = .29$ ,  $p < .001$ ) and posttest scores ( $r = .35$ ,  $p < .001$ ), and are still informative to the research questions.

**Revision activity.** The average activity score (i.e., number of correct answers) across all conditions was 4.41 ( $SD = 2.0$ ) out of the 12 items. There were no significant differences in activity scores across gender, major, or conditions. Similar to the prior knowledge assessment, reliability estimates were low for the activity questions ( $\alpha = .41$ ), but the activity was designed as an instructional tool, not a measurement tool. Participants' knowledge should have been changing throughout the activity.

*Photosynthesis misconceptions.* Percentages of misconception answers selected in the activity indicate that participants had misconceptions about photosynthesis and respiration. Percentages of specific misconception answers that were selected are outlined in *Table 1*. These percentages are likely underestimated, because question order was randomized and participants should have been less likely to select a misconception at the end of the activity, assuming the activity was effective.

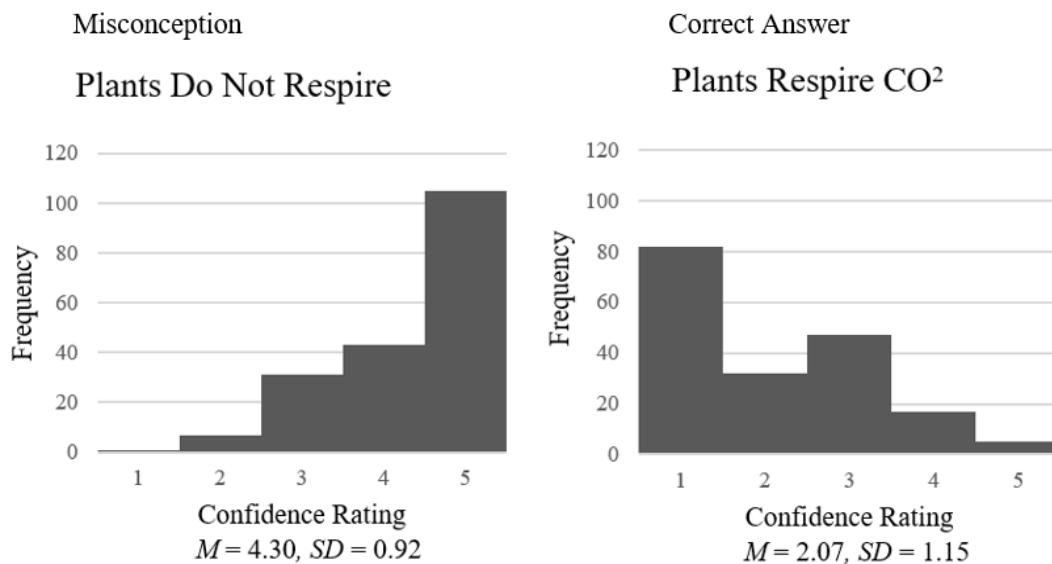
Table 1

*Percentages of Participants Indicating Specific Misconceptions in the Activity*

| Misconception   | Associated Answer Choice   | Question Type | Average Confidence | % that selected |
|---|--|---------------|--------------------|-----------------|
| Plants get food from the ground                         | The food comes in from the soil through the plant's roots  | Knowledge     | 3.93               | 21%             |
|   | Most ATP comes from the digestion of organic matter absorbed by the roots                                    | Knowledge     | 3.01               | 13%             |
|   | Absorption of organic substances from the soil via the roots   | Application   | 3.80               | 43%             |
| Plants do not respire                                   |                             | Knowledge     | 4.30               | 48%             |
|   | respiration takes place in animals only  | Knowledge     | 3.46               | 19%             |
|   | It will weigh the same because no biomass is produced  | Application   | 3.80               | 20%             |
| Respiration only takes place when photosynthesis is not | Respiration takes place in all plants only when there is no light energy                                     | Knowledge     | 4.17               | 33%             |
|   | Carbon dioxide/Oxygen, because plants only photosynthesize and don't respire in the presence of light energy | Application   | 3.19               | 26%             |
|   | Oxygen, because this gas is used in respiration when there is no light energy to photosynthesize             | Application   | 3.45               | 22%             |
|   | It is a process that doesn't take place in green plants when photosynthesis is taking place                  | Knowledge     | 3.56               | 8%              |
| Respiration is the same as breathing                    | It will weigh less because no photosynthesis is occurring  | Application   | 3.70               | 36%             |
|   | In the cells of the leaves only, because only leaves have special pores to exchange gas                      | Knowledge     | 4.04               | 26%             |
|   | In every plant cell, because every cell has pores to exchange gas  | Knowledge     | 3.43               | 24%             |
|   | It is the exchange of carbon dioxide and oxygen gases through plant stomata                                  | Knowledge     | 3.48               | 35%             |

Note: Confidence ratings are only reported for participants who selected that misconception.

*Confidence ratings.* Confidence ratings for selected misconception answers indicate the presence of misconceptions rather than guesses, because participants selected misconception answers with relatively high confidence. A misconception answer with a low confidence rating of 1 or 2 would indicate a guess, because confidence was on a scale of 1 to 5. Mean confidence ratings for selected misconception answers were greater than 3, whereas mean confidence ratings for unselected correct or unselected incorrect answers were less than 3. *Figure 2* demonstrates how confidence rating frequencies differed for a selected misconception answer and associated unselected correct answer. Cronbach Alpha analysis indicated the confidence measures were reliable (46 items;  $\alpha = .83$ ).



*Figure 2.* Histograms illustrating confidence in the misconception answer and the correct answer for participants who selected the misconception *plants do not respire* in activity question 2.

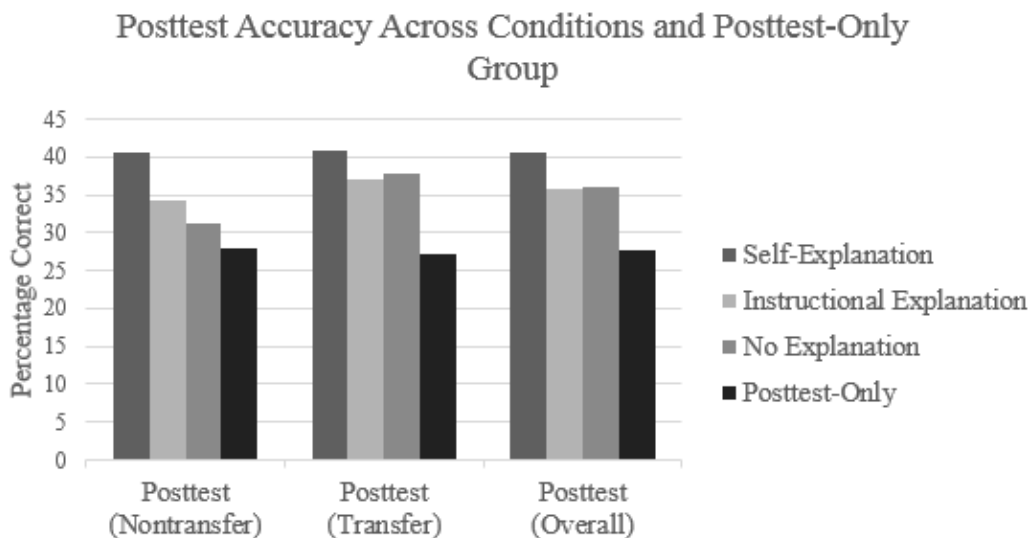
*Cognitive load.* Cognitive load scores across the 12 activity questions were averaged for each participant. Average cognitive load across all conditions was 3.20 ( $SD = 1.48$ ); averages are based on the 1 to 7 cognitive load scale, with 7 indicating very high cognitive load. There were no significant differences between gender or major across cognitive load averages. A one way

ANOVA indicated that average cognitive load was significantly different across conditions. The self-explanation condition ( $M = 3.92$ ;  $SD = 1.42$ ) had significantly higher average cognitive load scores than the no explanation condition ( $M = 3.14$ ,  $SD = 1.37$ ), and the no explanation condition had significantly higher average cognitive load scores than the instructional explanation condition ( $M = 2.65$ ,  $SD = 1.37$ ),  $F(2, 398) = 27.24$ ,  $p < .001$ . Measures of Cronbach's Alpha indicated the cognitive load measure was highly reliable (12 items;  $\alpha = .94$ ).

**Posttest.** Overall posttest scores were not significantly different across genders when controlling for prior knowledge,  $F(2, 296) = .13$ ,  $p = .66$ ). Thus, gender is collapsed across all analyses. Reliability estimates for the posttest were sufficient (24 items;  $\alpha = .71$ ). Thirty-four participants volunteered to participate during the second session of the study and only participated in the posttest. This posttest-only group served as baseline to compare the effects of the three activity conditions to.

*Comparison to posttest-only group.* To compare differences across posttest scores for the posttest-only group ( $N = 34$ ) and three conditions, a one way ANOVA using the Welch's  $F$  test was employed to account for unequal variances (Lix, Keselman, & Keselman, 1996). Results indicated significant differences across overall posttest scores, Welch's  $F(3, 433) = 8.63$ ,  $p < .001$ . Games-Howell post-hoc tests, which do not assume equal variances, indicated that the posttest-only group ( $M = 6.62$ ,  $SD = 2.65$ ) had significantly lower posttest scores than the self-explanation condition ( $M = 9.77$ ,  $SD = 4.61$ ), instructional explanation condition ( $M = 8.57$ ,  $SD = 3.75$ ) and no explanation condition ( $M = 8.63$ ,  $SD = 3.79$ ). Similar results were also found when Welch's  $F$  test was also conducted on scores for transfer questions,  $F(3, 433) = 5.20$ ,  $p = .002$ , and scores for non-transfer questions,  $F(3, 433) = 7.13$ ,  $p < .001$ . See *Figure 3* for a comparison of posttest scores across the posttest-only group and conditions.





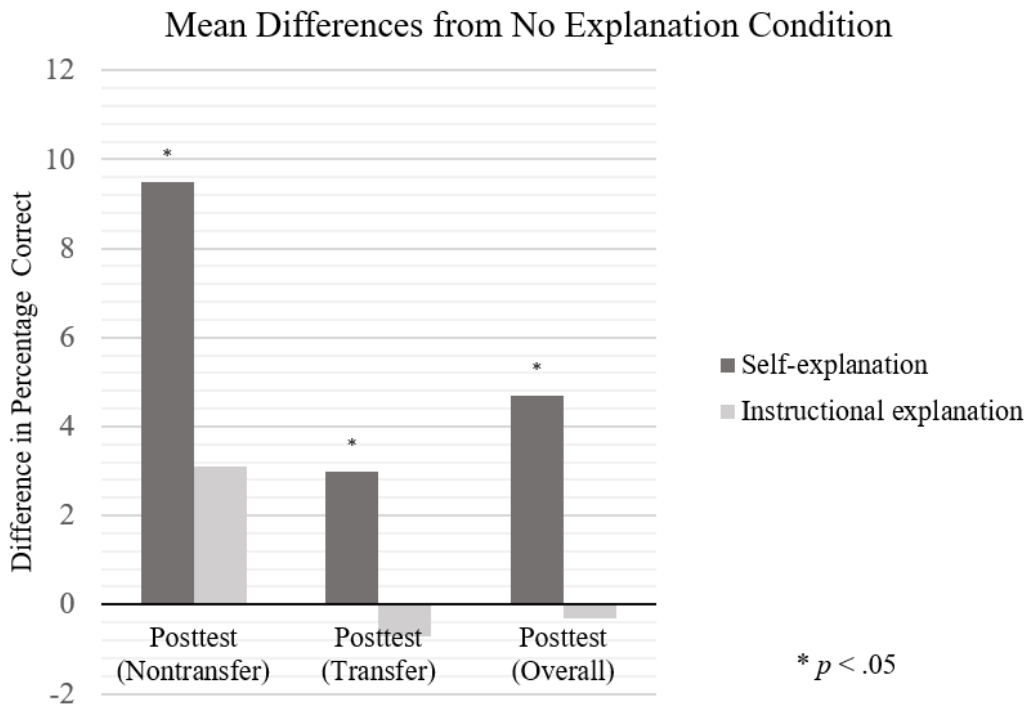
*Figure 3.* Accuracy for the nontransfer posttest questions, transfer posttest questions, and all posttest questions across the posttest-only group and three conditions.

## Research Questions

A number of analyses were employed to investigate the four research questions in this study. Prior to analyses, continuous independent variables, including prior knowledge scores and cognitive load scores, were mean-centered. Dummy coded variables for the self-explanation condition and instructional explanation condition were created, with the no explanation condition as the reference group. All assumptions concerning linearity, homoscedasticity, normality, and multicollinearity were met.

**Research Question 1.** To investigate how self-explanations and instructional explanations compared to no explanations, an ANCOVA was employed to compare the effects of condition after controlling for prior knowledge. There was a significant effect of condition on overall posttest scores,  $F(2, 399) = 7.07, p = .001$ . Pairwise comparisons indicated that the self-explanation group ( $M = 40.71, SD = 19.44$ ) had significantly higher posttest scores ( $p = .01$  and  $p = .01$ , respectively) than instructional explanation group ( $M = 35.71, SD = 15.63$ ) and no

explanation group ( $M = 35.98$ ,  $SD = 15.74$ ), but posttest scores for the instructional explanation group were not significantly different than the no explanation group ( $p = .99$ ). The same results were found when separately analyzing non-transfer posttest scores,  $F(2, 399) = 7.56$ ,  $p = .001$ , and transfer posttest scores,  $F(2, 399) = 3.51$ ,  $p = .03$ . It should be noted that for overall posttest scores and transfer posttest scores, means for the instructional explanation group were lower than means in the no explanation group, but not significantly. Mean comparisons of conditions can be seen in *Figure 4*.

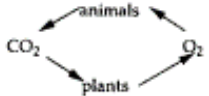


*Figure 4.* Differences in posttest accuracy compared to the No Explanation condition.

To provide insight into the conceptual change that is reflected in posttest scores, Table 2 provides the percentages of misconception answers selected in the self-explanation condition (SE), instructional explanation condition (IE) and no explanation condition (No Ex).

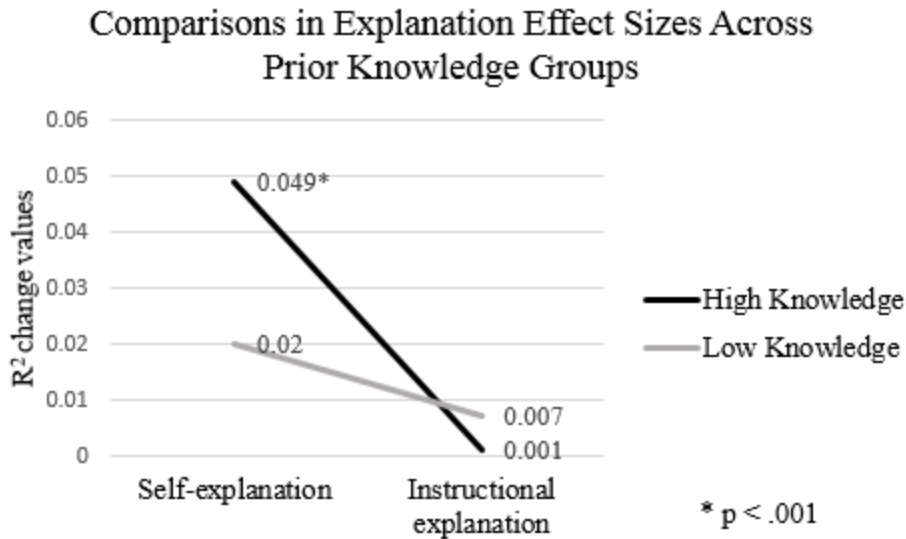
Table 2

*Percentages of Participants in Each Condition Indicating Misconceptions on the Posttest*

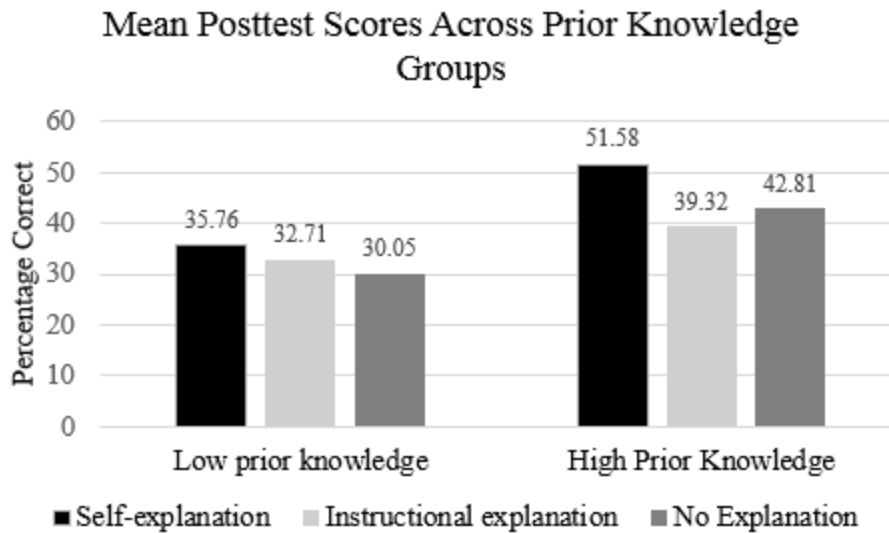
| Misconception   | Associated Answer Choice   | Activity<br>%<br>(n=400) | Posttest Percentages |               |                  |
|---|--|--------------------------|----------------------|---------------|------------------|
|   |  |                          | SE<br>(n=118)        | IE<br>(n=140) | No Ex<br>(n=145) |
| Plants get food from the ground                         | The food comes in from the soil through the plant's roots  | 21%                      | 14%                  | 19%           | 28%              |
|   | Most ATP comes from the digestion of organic matter absorbed by the roots                                    | 13%                      | 6%                   | 6%            | 9%               |
|   | Absorption of organic substances from the soil via the roots   | 43%                      | 23%                  | 24%           | 21%              |
| Plants do not respire                                   |                             | 48%                      | 28%                  | 37%           | 45%              |
|   | respiration takes place in animals only  | 19%                      | 11%                  | 19%           | 16%              |
|   | It will weigh the same because no biomass is produced  | 20%                      | 9%                   | 13%           | 12%              |
| Respiration only takes place when photosynthesis is not | Respiration takes place in all plants only when there is no light energy                                     | 33%                      | 26%                  | 34%           | 30%              |
|   | Carbon dioxide/Oxygen, because plants only photosynthesize and don't respire in the presence of light energy | 26%                      | 13%                  | 19%           | 21%              |
|   | Oxygen, because this gas is used in respiration when there is no light energy to photosynthesize             | 22%                      | 18%                  | 16%           | 18%              |
|   | It is a process that doesn't take place in green plants when photosynthesis is taking place                  | 8%                       | 9%                   | 11%           | 7%               |
|   | It will weigh less because no photosynthesis is occurring  | 36%                      | 28%                  | 28%           | 25%              |
| Respiration is the same as breathing                    | In the cells of the leaves only, because only leaves have special pores to exchange gas                      | 26%                      | 18%                  | 16%           | 21%              |
|   | In every plant cell, because every cell has pores to exchange gas  | 24%                      | 17%                  | 26%           | 24%              |
|   | It is the exchange of carbon dioxide and oxygen gases through plant stomata                                  | 35%                      | 30%                  | 30%           | 34%              |

**Research Question 2.** To investigate whether the effects of self-explanations and instructional explanations varied as a function of prior knowledge levels, participants were separated into prior knowledge categories in order to obtain and compare effect sizes for each condition within each prior knowledge groups. This is the suggested method for examining expertise reversal effects (Mayer, 2001; Kalyuga, 2007). Using cut points to create three equal groups, participants were divided into three prior knowledge groups based on their prior knowledge assessment scores. A one way ANOVA indicated that the low prior knowledge group ( $M = 2.43$ ), moderate prior knowledge group ( $M = 4.51$ ) and high prior knowledge group ( $M = 7.38$ ) all had significantly different prior knowledge assessment scores,  $F(2, 400) = 656.52, p < .001$ . This analysis compares the high prior knowledge and low prior knowledge groups.

To obtain effect sizes for each condition across high and low prior knowledge groups, two separate regression analyses were conducted on each prior knowledge group with dummy coded condition variables as predictors of posttest scores. Results indicated that in the low prior knowledge group, neither explanation condition significantly predicted posttest scores,  $F(2, 133) = 1.87, p = .16$ . In the high prior knowledge group, the self-explanation condition significantly predicted posttest scores ( $\beta = .21, p < .001$ ), but the instructional explanation condition did not ( $\beta = -.03, p = .77$ ),  $F(2, 133) = 11.56, p < .001$ .  $R^2$  change values for each explanation condition were obtained and a comparison of these effect sizes can be found in *Figure 5a*. Although self-explanations were not a significant predictor for low prior knowledge participants, no expertise reversal occurred; self-explanations were associated with the highest posttest scores in both high and low prior knowledge groups. See *Figure 5b* for a comparison of means across conditions for high and low prior knowledge groups.



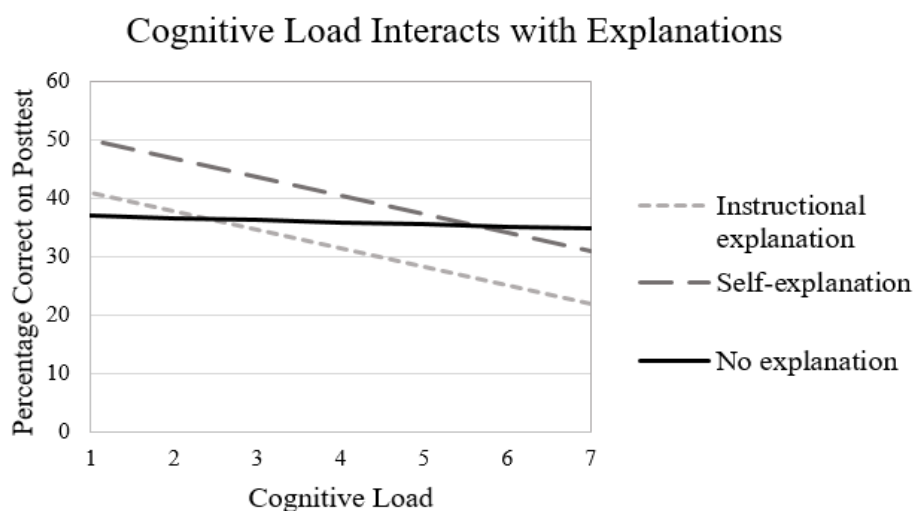
*Figure 5a.* Effect sizes for the two regression models conducted on the high prior knowledge group and low prior knowledge group.



*Figure 5b.* Mean posttest scores for the high and low prior knowledge groups across conditions.

**Research Question 3.** To investigate if cognitive load during the activity affected learning overall, as well as to determine how cognitive load affected learning in each condition, I employed a linear regression model that controlled for the main effects of prior knowledge and condition (two dummy-coded variables) before assessing whether the main effects of cognitive

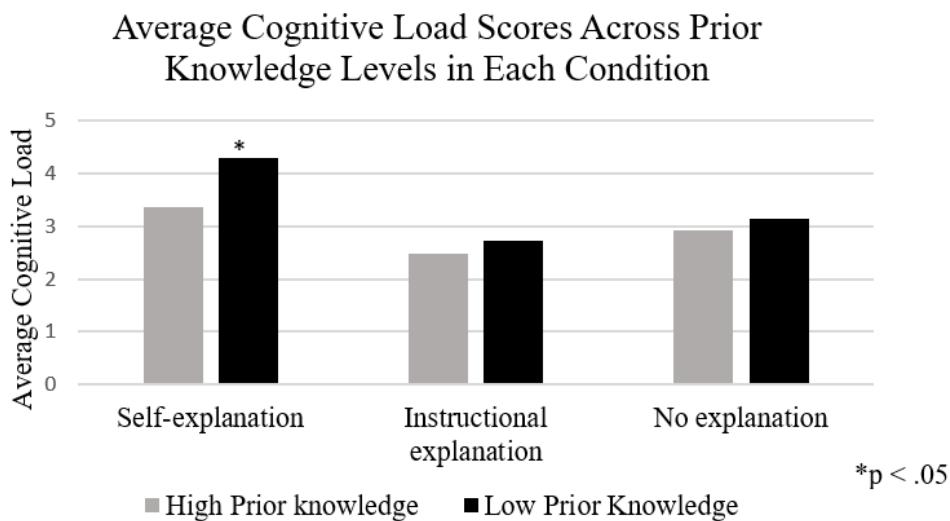
load, the interacting effect of cognitive load and the self-explanation condition, and the interacting effect of cognitive load and instructional explanations were predictive of posttest accuracy. The model including all six variables significantly predicted posttest scores,  $F(6, 394) = 13.22, p < .001$ . After controlling for prior knowledge ( $\beta = -.33, p = .00$ ), condition ( $\beta = .38, p = .009$  and  $\beta = .21, p = .09$ ), and the main effect of cognitive load ( $\beta = .01, p = .94$ ), the interaction between cognitive load and self-explanations ( $\beta = -.27, p = .08$ ) approached significance, and the interaction between cognitive load and instructional explanations ( $\beta = -.25, p = .03$ ) significantly predicted posttest scores. In both explanation conditions, increased cognitive load predicted lower posttest scores. See *Figure 6* for a graphical depiction of the effects of cognitive load across condition.



*Figure 6.* The linear relationship between cognitive load scores and posttest scores across conditions.

**Research Question 4.** To investigate how cognitive load during self-explanations and instructional explanations related to prior knowledge, two separate bivariate correlations were run on cognitive load and prior knowledge scores for each condition. Results indicated a significant and negative correlation between cognitive load and prior knowledge scores in the

self-explanation ( $r = -.28, p = .003$ ), but not in the instructional explanation condition ( $r = -.07, p = .43$ ). A full factorial ANOVA including prior knowledge, cognitive load, and condition indicated a significant three-way interaction between the variables,  $F(2, 360) = 2.87, p = .04$ . Separate ANOVA's on each condition with cognitive load as the dependent variable and prior knowledge category as the independent variable indicated that cognitive load was significantly higher in the low prior knowledge group ( $M = 4.29$ ) than the high prior knowledge group ( $M = 3.38$ ),  $F(2, 115) = 3.50, p = .03$  for participants in the self-explanation condition, but there was no significant difference in cognitive load across high and low prior knowledge group in the instructional explanation condition,  $F(2, 127) = .17, p = .84$ , or the no explanation condition,  $F(2, 116) = 1.41, p = .25$ . Only the self-explanation condition was prone to inducing particularly high cognitive load in participants with low prior knowledge levels. See *Figure 7* for a graphical depiction of cognitive load scores across prior knowledge groups and conditions.



*Figure 7.* Average cognitive load scores that participants in the high prior knowledge group and low prior knowledge group reported for each condition.

**Post-hoc analysis.** A post-hoc analysis of participants' self-explanations was conducted to investigate if the negative effects of low prior knowledge on self-explaining could be accounted for by the general quality of the explanations participants provided. With the observation of a number of explanations that simply said "I don't know," it seemed likely that low knowledge participants were more likely to make these low quality explanations. Each explanation was coded for general quality on a scale of 1 to 3. Explanations received a rating of 1 if they did not address the content, but rather expressed that the learner *did not know* why the answer was correct (e.g., "I don't know") or stated *why* the learner chose the answer (e.g., "the others are wrong"). Explanations received a rating of 2 if they explained the correct answer in six words or less (e.g., "Oxygen goes to plants and animals"). Explanations received a rating of 3 if they explained the correct answer in more than six words (e.g., "Animals and plants alike create CO<sub>2</sub>. Plants cycle organic carbon into oxygen. Animals and plants both cycle oxygen"). Totals of participants' 12 explanation scores were then calculated. Because explanations were not coded for accuracy, but rather for length and whether they addressed content, summed explanation scores served as a general measure of engagement in the self-explanation task.

Cognitive load was not correlated with participants' explanation scores ( $p = .19$ ), suggesting that neither high cognitive load nor low cognitive load was not associated with disengagement in the task. Explanation scores were slightly correlated with prior knowledge scores ( $r = .20$ ,  $p = .03$ ), but a one way ANOVA did not indicate any significant differences in explanation scores across prior knowledge groups ( $p = .31$ ). When added to a linear regression model predicting posttest scores for the self-explanation condition, self-explanation scores explained an addition 8% of variance in posttest scores after controlling for prior knowledge ( $R^2 = .20$ ,  $F(2, 115) = 13.99$ ,  $p < .001$ ). In the self-explanation condition, it appeared that



engagement in the task predicted learning but was unrelated to cognitive load and prior knowledge measures. Posttest scores were significantly higher for participants who were more engaged in self-explaining.

### **Discussion**

The study presented here employed a computer-based revision activity to investigate the effects of prior knowledge levels and explanation tasks – and the interactions between them – on conceptual change in undergraduate biology students. This study focused specifically on the effects of generating explanations and reading explanations on cognitive load in learners with different prior knowledge levels and the subsequent conceptual change of photosynthesis and respiration misconceptions. The primary aim was to identify which explanation tasks worked best for students at particular prior knowledge levels. In line with prior research, findings indicated that undergraduate biology students hold common instruction-resistant misconceptions pertaining to photosynthesis and respiration (Anderson, Shelton, & Dubay, 1990; Coley & Tanner, 2015; Prossner, 1994; Södervik, Virtanen, & Mikkilä-Erdmann, 2015; Songer & Mintzes, 1994), and prompting students to explain the correct answers to questions, which have misconceptions embedded in them, promotes conceptual change (Chi, 2008; Williams, Lombrozo, Hsu, Huber, & Kim, 2016). Self-explanations are especially beneficial to students with sufficient prior knowledge levels and are less beneficial for students with low levels of prior knowledge (Atkinson, Renkl & Merrill, 2003; Kalyuga, Ayres, Chandler, & Sweller, 2003; Leppink et al., 2012; Paas & Van Gog, 2006; Renkl, Stark, Gruber & Mandl, 1998; Roy & Chi, 2005). Although instructional explanations typically benefit learning in students with low prior knowledge levels (Atkinson, Renkl, & Merrill, 2003; Hilbert, Schworm, & Renkl, 2004), the instructional explanations in this study had no effects on learning. Similar to when instructional

or self-explanation tasks are used for knowledge building (Sweller, 2008), both explanation tasks in this study were prone to cognitively overloading students. High cognitive load in the self-explanation could be explained by low prior knowledge levels, but prior knowledge was not related to cognitive load in the instructional explanation condition or no explanation condition. The discussion that follows explains the main findings regarding the self-explanation, instructional explanation, and no explanation conditions in this study.

*Self-explanations.* Findings clearly indicate that prompting students to generate explanations of the correct answers to activity questions produced the greatest learning gains relative to reading explanations and just answering questions with feedback. Inducing meaningful cognitive conflict in learners is an essential step in conceptual change, and self-explanations promote conceptual change by making learners aware of conflicts between their prior knowledge and new information (Chi, 2008). Anecdotal evidence from the self-explanations students provided in this study supports this idea; self-explaining encouraged some students to engage with and reflect on their cognitive conflict. For instance, consider the following explanation provided by a student: “I’m not sure of how to explain why D is correct. I felt certain that water or sunlight were the keys to growth in the plant kingdom. I’m not sure why this is the correct answer. If I had to guess it is because the plant is letting off CO<sub>2</sub> but not taking anything in. Therefore it will weigh less.” In this explanation, the student describes her cognitive conflict. Despite apparent uncertainty, the student used prior knowledge to correctly explain the answer. When students with sufficient prior knowledge engage in self-explaining, they activate the correct knowledge in memory, thereby strengthening their memory for that knowledge. They also activate their misconception and encode an instance of that knowledge being incorrect, which can be remembered later when that misconception is reactivated in memory (Kendeou &

O'Brien, 2014). However, not all students in this study produced meaningful explanations that elicited these processes.

Before discussing the effects of prior knowledge on learning through self-explaining, the knowledge levels considered in this study should be put into context. In this study, "high" prior knowledge was relative. There were no experts or students with high levels of biology knowledge. This sample consisted of novices, all of whom were in introductory-level courses. The findings regarding prior knowledge differences in this study more accurately demonstrate the effects of having low prior knowledge and having moderate prior knowledge. For the sake of clarity, I still refer to them as high and low prior knowledge groups in this discussion.

Current findings indicate that self-explaining is less beneficial for students with low knowledge levels. Previous research on self-explaining suggests low prior knowledge learners may be less able to generate explanations that engage them in the positive learning strategies associated with self-explaining, like connecting new knowledge and prior knowledge and generating inferences to connect them (Chi et al., 1989), and low prior knowledge learners may also generally engage less with self-explaining (Roy & Chi, 2005). However, there were no significant differences in engagement across low and high prior knowledge learners. Rather, low prior knowledge learners reported particularly high cognitive load when engaging in self-explaining, and high cognitive load was associated with diminished learning through the activity. Despite this cognitive overload, self-explaining still produced greater learning gains compared to instructional explanations. This suggests that instead of starting students with instructional explanations and transitioning them to self-explanations as their knowledge level increases (Atkinson, Renkl, & Merrill, 2003; Hilbert, Schworm, & Renkl, 2004), that low prior knowledge students should start with self-explaining tasks that are highly supported. For instance, prior

work suggests that teaching low knowledge students how to produce meaningful explanations, which can be achieved by a computer-based tutoring system, can support students enough to negate the negative effects of low prior knowledge (Conati & VanLehn, 2000; O'Reilly, Best, & McNamara, 2004).

*Instructional explanations.* The instructional explanations in this study had no effects on learning, and trends in means and effect sizes suggest that instructional explanations actually negated some of the learning that happened through answering questions and receiving correct answer feedback (i.e., no explanation condition) in high prior knowledge learners. Similar to self-explanations, higher cognitive load was associated with diminished learning gains. Unlike self-explanations, low prior knowledge and high prior knowledge groups had similar levels of cognitive load when reading instructional explanations. Students across knowledge levels reported that the explanations were easy to understand, but considering that no one benefited from the explanations, this subjective feeling of understanding may not be fruitful for conceptual change. Findings suggest that students simply read the instructional explanations without reflecting on how their knowledge conflicted with the information presented in them – if students had reflected on a cognitive conflict, then the instructional explanations should have had positive effects on learning. The low overall cognitive load ratings associated with the instructional explanations may imply that the instructional explanations did not make students aware of a conflict between their knowledge and the information in the text. Further, if the instructional explanations did induce cognitive conflict, they did not sufficiently guide students to resolve them through conceptual change. Students are used to reading instructional explanations, but they may need practice and additional support, beyond the direct and indirect refutations included in my instructional explanations, to realize when and how instructional explanations

conflict with their prior (inaccurate) understanding.

*Revision activity without explanations.* The no explanation condition in this study served as a baseline to compare the effects of self-explanations and instructional explanations to. However, the incidental posttest-only group served as an addition baseline to compare with the effects of the no explanation condition. Without the presence of any explanation prompts, the no explanation condition was simply a retrieval practice task, and the cognitive load measure associated with the no explanation condition prompted students to reflect on the correct answer feedback (i.e., “how hard was it for you to understand the correct answer?”) Findings indicated that practicing retrieval and mentally reflecting on the correct answer feedback resulted in a significant amount of learning relative to the posttest-only group. Although retrieval practice is not a typical strategy used in conceptual change instruction, it promoted conceptual change in both high and low prior knowledge learners in this study. Unlike the explanation conditions, the retrieval practice in the no explanation condition was not prone to inducing cognitive overload. It also requires a certain level of engagement from the learner, because learners must actively retrieve prior knowledge from memory. Thus, it may be a particularly useful revision task to include in computer-based conceptual change instruction.

*The utility of multiple-choice misconception questions.* The activity designed for this study, which prompted participants to rate their confidence in each answer choice, provided the opportunity to confirm that the multiple-choice items were not inflating misconception rates with guesses. Without associated confidence ratings, forced-choice assessments are unable to distinguish between guesses and true misconceptions (Hughes, Lyddy, & Kaplan, 2013). Students were confident in the accuracy of the misconception answers they selected, suggesting that misconceptions targeted by the activity were relevant in this population. Including

misconceptions in answer choices, as long as they are supported by relatively high confidence judgments, provides an effective method for measuring misconception rates in a computer-based environment.

Findings also support prior work suggesting that learners may indicate a specific misconception in one question but not in another (Eylon, Ben-Zvi, & Silberstein, 1987), supporting the idea that multiple opportunities (i.e., questions) to indicate a particular misconception should be provided. The application questions included in the activity, which had students apply their conceptual understanding to a specific situation, were particularly effective at activating misconceptions. For instance, for the misconception that *plants get their food from the ground*, 43% of students selected this misconception in an application question that asked them to predict where a plant in a particular situation would get the energy for growth. Only 21% of participants selected this misconception in a knowledge-based question that generally asked them where plants get their food. The disparity between misconception rates indicated on application and knowledge questions suggests that students memorize facts about photosynthesis and respiration during instruction but do not incorporate this knowledge into their conceptual understanding (Tas, Cepni, & Kaya, 2012). In order to increase the likelihood of an existing misconception being indicated in a multiple-choice activity, the misconception should be embedded within multiple questions, which should include application questions that cannot be answered using memorized facts.

There are several limitations to this study, the most significant limitation being the reliability issues with the prior knowledge measure. Scores on the prior knowledge assessment were particularly low, which indicates that the difficulty level of the assessment was not aligned with the sample, or that students were not trying their best on the questions. However, the

difficulty of the prior knowledge assessment does not explain the lack of correlation across questions. The low reliability of the prior knowledge assessment likely resulted in underestimation of the effects of students' actual prior knowledge levels.

Another limitation to this study concerned the instructional explanations. While the self-explanations that students generated provided a general measure of their engagement in the task, there was no such measure for instructional explanations. Without a measure of engagement for the instructional explanations, there was no way to empirically parse apart the effects of the instructional explanations and whether students were attending to those instructional explanations. A final limitation to this study is that students were not externally motivated to learn the content; they were not graded on accuracy, nor were they preparing to take any sort of formative assessment on the content. Thus, the results presented here are likely conflated with individual differences in students' motivation to learn.

In conclusion, the study presented here demonstrates that computer-based activities can effectively promote conceptual change in undergraduate students. More specifically, activities that prompt students to retrieve knowledge and construct knowledge, like retrieval practice and self-explaining, can engage students in the conceptual change process; whereas instructional explanations, even when embedded in retrieval practice activities, may not effectively engage students in conceptual change in a computer-based environment. Multiple-choice activities that contain known misconceptions in the answer choices are an effective way to detect misconceptions in students when they are accompanied by confidence judgments. This type of activity can also provide an opportunity to adapt instruction based on whether learners' incorrect answers are the result of a misconception (i.e., incorrect answer selected with high confidence) or lack of knowledge (i.e., incorrect answer selected with low confidence). If a misconception is

indicated, instruction could adapt by providing an activity that promotes cognitive conflict, like self-explaining. This study demonstrates that there are opportunities for this type of adaptation, and further research on the effects of prior knowledge on revision tasks could provide greater insight into how conceptual change instruction could be optimized across learners.



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## APPENDICES

### Appendix A

#### Prior Knowledge Assessment Questions

Correct answers are indicated in **bold**.

- 1) Imagine that a scientist discovers a mutant plant seedling that appears to lack stomata. What would be the effect of this?
  - A) **CO<sub>2</sub> would not be able to enter the plant as a reactant for photosynthesis**
  - B) Water would not be able to enter the plant as a reactant for photosynthesis
  - C) Visible wavelengths of light would be unable to reach the chloroplasts
  - D) Additional ATP would be produced by the seedling, and the plant would grow taller
  
- 2) Albino corn has no chlorophyll. You would expect albino corn seedlings to
  - A) capture light energy in the white end of the visible light spectrum
  - B) fail to thrive because they cannot capture light energy**
  - C) synthesize glucose indefinitely, using stored ATP and NADPH
  - D) switch from the C<sub>4</sub> pathway to the CAM pathway
  - E) use accessory pigments such as carotenoids to capture light
  
- 3) The energy required for photosynthesis to occur is
  - A) glucose
  - B) ultraviolet light
  - C) visible light**
  - D) air
  - E) oxygen
  
- 4) In the chloroplast, energy in sunlight is passed around different chlorophyll molecules until it reaches a specific chlorophyll molecule that can transfer energy in sunlight to an energized electron. This chlorophyll molecule is called the
  - A) reaction center**
  - B) photoelectric point
  - C) electron carrier molecule
  - D) accessory pigment
  - E) nucleus
  
- 5) Carotenoid pigments are found in the
  - A) mitochondria
  - B) stroma of the chloroplasts
  - C) thylakoid membranes of the chloroplasts**
  - D) nucleus

- 6) The replacement electrons for the reaction center of photosystem II come from
- A) photosystem I
  - B) H<sub>2</sub>O**
  - C) glucose
  - D) O<sub>2</sub>
  - E) NADPH
- 7) Which sequence accurately describes the flow of electrons in photosynthesis?
- A) Photosystem I → photosystem II → H<sub>2</sub>O → NADP
  - B) Photosystem II → photosystem I → NADP → H<sub>2</sub>O
  - C) H<sub>2</sub>O → photosystem II → photosystem I → NADP**
  - D) Photosystem I → photosystem II → NADP → H<sub>2</sub>O
  - E) H<sub>2</sub>O → photosystem I → photosystem II → NADP
- 8) The ATP and NADPH synthesized during the light reactions are
- A) dissolved in the cytoplasm
  - B) transported to the mitochondria
  - C) pumped into a compartment within the thylakoid membrane
  - D) transported into the nucleus
  - E) moved to the stroma**
- 9) What is produced in the electron transport system associated with photosystem II?
- A) NADPH
  - B) ATP**
  - C) Glucose
  - D) O<sub>2</sub>
  - E) CO<sub>2</sub>
- 10) Suppose you are studying photosynthesis in a research lab. You grow your plants in a chamber with a source of water that has a radioactively labeled oxygen atom. What photosynthetic product will be radioactive?
- A) ATP
  - B) Glucose
  - C) O<sub>2</sub> gas**
  - D) NADPH
  - E) CO<sub>2</sub> gas
- 11) You are carrying out an experiment on several aquatic plants in your fish tank. You decide to expose two of the plants to green light and two to blue light. You want to determine which type of light is best for the light reactions, so you decide to record the amount of oxygen bubbles produced to reach your conclusions. Which of the following results would be expected?
- A) There would be more bubbles from the plants in green light than from those in blue light.
  - B) There would be more bubbles from the plants in blue light than from those in green light.**
  - C) There would be the same number of bubbles from plants in blue or green light.

- D) No bubbles would be produced in either green light or blue light.
- 12) Photosynthesis could be considered as a series of biophysical and biochemical reactions allowing:
- A) water photolysis and subsequent flow of protons along a donor-acceptor chain until oxidation of NADPp
  - B) utilization for biomass production of part of the energy resulting from the process of fusion of hydrogen atoms in the Sun
  - C) electron transfer from a molecule of negative redox potential (water) to another molecule of positive redox potential (NADPp)**
  - D) reduction of organic carbon, producing inorganic carbon
- 13) If water labeled with  $^{18}\text{O}$  is used in photosynthesis by a green plant, the  $^{18}\text{O}$  will be found in:
- A) starch in chloroplasts
  - B) carbon dioxide produced in respiration
  - C) oxygen produced**
  - D) cellulose in the cell wall
- 14) Which of the following statements about the light reactions of photosynthesis is FALSE?
- A) The splitting of water molecules provides a source of electrons.
  - B) Chlorophyll (and other pigments) absorbs light energy, which excites electrons.
  - C) An electron transport chain is used to create a proton gradient.
  - D) NADPH becomes oxidized to NADP<sup>+</sup>.**
  - E) ATP is formed.
- 15) The ATP and NADPH synthesized during the light reactions are
- A) dissolved in the cytoplasm.
  - B) transported to the mitochondria.
  - C) pumped into a compartment within the thylakoid membrane.
  - D) transported into the nucleus.
  - E) moved to the stroma.**

## Appendix B

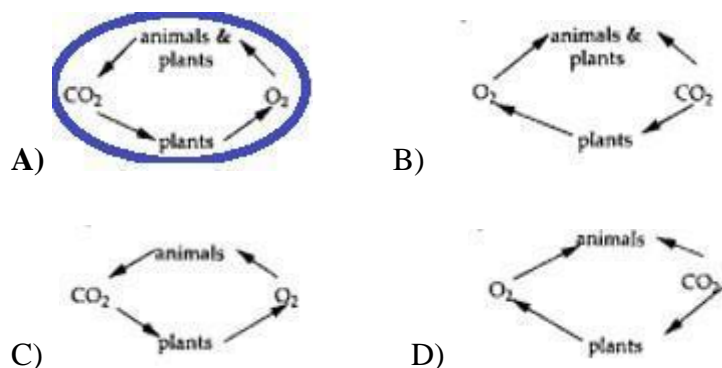
### Revision Activity Questions

Correct answers are indicated in **bold**

1) Where does the food that a plant needs come from?

- A) The food comes in from the soil through the plant's roots.
- B) The food comes in from the air through the plant's leaves.
- C) The plant makes its food from carbon dioxide and water.**
- D) The plant makes its food from minerals and water.

2) Which of the following drawings shows the cycling of carbon dioxide and oxygen in nature?



3) Which of the following comparisons between the process of photosynthesis and respiration is correct?

- A) Photosynthesis takes place in green plants only, and respiration takes place in animals only.
- B) Photosynthesis takes place in all plants, and respiration takes place in animals only.
- C) Photosynthesis takes place in green plants in the presence of light energy, and respiration takes place in all plants and animals at all times.**
- D) Photosynthesis takes place in green plants the presence of light energy, and respiration takes place in all plants, only when there is no light energy, and all the time in animals.

4) Respiration in plants takes place in

- A) The cells of the roots only, because only roots have small pores to breath
- B) The cells of the roots only, because only roots need energy to absorb water
- C) In every plant cell, because every cell has pores to exchange gas.
- D) In every plant cell, because all living cells need energy to live**
- E) In the cells of the leaves only, because only leaves have special pores to exchange gas

5) In the presence of sunlight, what gas is given off in the largest amounts by green plants?

- A) Carbon Dioxide, because plants only photosynthesize and don't respire in the presence of light energy.
- B) Oxygen, because plants only photosynthesize and don't respire in the presence of light energy.
- C) Oxygen, because it is a byproduct given off by plants when respiring.
- D) Oxygen, because it is a byproduct given off by plants when photosynthesizing**

- 6) Which gas is taken by green plants in large amounts when there is no light energy at all?
- A) Carbon dioxide, because it is used in photosynthesis, which occurs in green plants all the time
  - B) Carbon dioxide, because it is used in photosynthesis which occurs in green plants when there is no light energy at all
  - C) Oxygen, because this gas is used in respiration which only occurs in green plants when there is no light energy to photosynthesize
  - D) Oxygen, because this gas is used in respiration which takes place continuously in green plants**
- 7) A mature maple tree can have a mass of 1 ton or more (dry biomass, after removing the water), yet it starts from a seed that weighs less than 1 gram. Which of the following processes contribute the most to this vast increase in biomass?
- A) Absorption of organic substances from the soil via the roots.
  - B) Incorporation of H<sub>2</sub>O from the soil into molecules by green leaves
  - C) Absorption of solar radiation into green leaves
  - D) Incorporation of CO<sub>2</sub> gas from the atmosphere into molecules by green leaves**



Results: 1.48g

3.28g

1.17g

The following question is based on this experiment: Three batches of radish seeds, each with a starting weight of 1.5g (dry), were placed in petri dishes and provided only with light or water or both, as shown in the photo. After 1 week, the material in each dish was dried and weighed. The results are shown below each petri dish.

- 8) Where did the mass go that was lost by the seedlings in the "No light, Water" treatment?
- A) It was converted to CO<sub>2</sub> and H<sub>2</sub>O and then released.**
  - B) It was converted to heat and then released.
  - C) It was converted into ATP molecules.
  - D) It was eliminated from the roots as waste material.
  - E) It was converted to starch.
- 9) A potted geranium plant sits in a windowsill, absorbing sunlight. After I put this plant in a dark closet for a few days (but keeping it watered as needed), will it weigh more or less



(discounting the weight of the water) than before I put it in the closet?

- A) **It will weigh less because it is still respiring**
- B) It will weigh less because no photosynthesis is occurring.
- C) It will weigh more because the Calvin cycle reactions continue.
- D) It will weigh the same since no biomass is produced

10) A potted geranium plant sits in a windowsill absorbing sunlight. How does a root cell (which is not exposed to light) obtain energy in order to perform cellular work such as active transport across its membrane?

- A) ATP is made in the leaves via photosynthesis and moved to the root.
- B) **Sugar is made in the leaves via photosynthesis and moved to the root.**
- C) The root cell makes sugar using the dark reactions (Calvin cycle) of photosynthesis.
- D) The root cell makes ATP by photosynthesis and cellular respiration

11) Which of the following best describes how a plant cell gets the energy it needs for cellular processes?

- A) The chloroplasts provide all the ATP needed by the plants.
- B) In the light, the ATP comes from the chloroplasts, in the dark, from mitochondria.
- C) Most ATP comes from digestion of organic matter absorbed by roots, some comes from chloroplasts.
- D) **The sugars produced in photosynthesis are broken down during respiration to make ATP.**

12) Which of the following is the most accurate statement about respiration in green plants?

- A) It is a chemical process by which plants manufacture food from water and carbon dioxide.
- B) **It is a chemical process in which energy stored in food is released using oxygen.**
- C) It is the exchange of carbon dioxide and oxygen gases through plant stomates.
- D) It is a process that doesn't take place in green plants when photosynthesis is taking place.

## Appendix C

### Instructional Explanations

#### *Question 1*

Plants don't 'get food' from anywhere. Plants make their own food through photosynthesis. During photosynthesis, carbon dioxide and water react together in the presence of light energy and chlorophyll to make glucose. The glucose is converted into starch, fats and oils for storage. This food provides energy for them to carry out cellular processes.

#### *Question 2*

Plants use carbon dioxide in photosynthesis, which in turn produces oxygen as a byproduct. The oxygen produced during photosynthesis is used in cellular respiration. Almost all living things, including plants, get energy from cellular respiration. Cellular respiration then produces carbon dioxide as a byproduct. This carbon dioxide moves into the leaves of plants and the cycle continues.

#### *Question 3*

Explanation: Photosynthesis only takes place where there is chlorophyll (only found in green plants) and light energy. However, respiration is taking place in plants at all times, because it does not require light energy. The plant can store the sugars made in photosynthesis and continue to synthesize them through respiration at night. Respiration and photosynthesis can take place simultaneously in plants, even within the same cells. Continuous cellular respiration is necessary to keep cells alive, so it is occurring in plants and animals at all times.

#### *Question 4*

The metabolic energy produced by cellular respiration allows cells to carry out the basic functions needed to stay alive. Cellular respiration combines oxygen and the glucose created during photosynthesis to produce this usable energy (ATP). While cells can cooperate to get oxygen and glucose to other cells, but they cannot donate ATP to other cells; each cell must make its own ATP through respiration. If a cell doesn't make its own ATP, it won't be able to carry out cellular processes, eventually causing it to die.

#### *Question 5*

Green plants will photosynthesize in the presence of sunlight. During photosynthesis, the energy from the sun splits water molecules into hydrogen and oxygen. While some of the Oxygen molecules are then used to synthesize ATP, most are released back into the air.

#### *Question 6*

Only respiration, not photosynthesis, continues to take place in plants in the absence of light energy. In fact, respiration is taking place all the time. This includes both during photosynthesis and in the absence of photosynthesis. Oxygen is required for respiration, so plants will continue to take in large amounts of oxygen at night in order to respire. Thus, oxygen is taken by green plants in large amounts when there is no light energy.

#### *Question 7*

While solar radiation provides the energy necessary to make sugars through photosynthesis, the

mass that makes up those sugar molecules comes from the carbon and oxygen atoms originally contained in atmospheric carbon dioxide. The added mass comes from the CO<sub>2</sub> molecules taken in by the plants leaves. Some minerals from the soil can account for a very small amount of biomass increase, but most of the mass comes from the carbon in CO<sub>2</sub>.

*Question 8*

CO<sub>2</sub> and H<sub>2</sub>O are both waste products of respiration. The seeds in the “No light, Water” treatment would have been respiring throughout the experiment, because respiration does not require light. Since the seeds could not photosynthesize without light, the only byproducts released would have been from respiration.

*Question 9*

The plant will weigh less, because it will continue to go through cellular respiration in the dark. During cellular respiration CO<sub>2</sub>, which has mass, is given off. Since the plant cannot photosynthesize in the dark and gain mass, it will continue to lose mass through respiration in the absence of light energy.

*Question 10*

Roots cannot photosynthesize, because they are not exposed to light energy and do not (typically) contain chlorophyll. Since roots can't produce sugars through photosynthesis, they must get sugars from plant cells that do photosynthesize. The plant can coordinate to transport sugars to root cells, but the plant cannot transport ATP cells. Thus, root cells will receive sugars from photosynthetic cells and create ATP through their own respiration.

*Question 11*

Chloroplasts are the energy factories that produce sugars through photosynthesis. These sugars are used by respiration to make ATP. This ATP provides the usable energy required for the cellular processes that are necessary for cells to stay alive. However, the chloroplasts do not produce the ATP themselves, rather they produce the sugar needed for respiration to make ATP.

*Question 12*

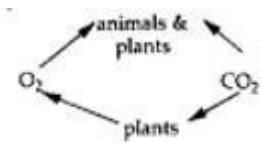
Respiration consists of a complicated series of chemical reactions that turn the sugars made into ATP. In the first stage, glucose is oxidized, and the chemical potential energy of its bonds is transferred to the chemical potential bonds of an ATP molecule. The ATP molecule can then be transported throughout the cell where its stored energy is used to complete various tasks within the cell. This process is taking place all the time and provides the metabolic energy required by all cells to function and stay alive.

## Appendix D

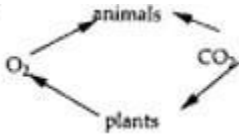
### Posttest Questions

Correct answers are in **bold**

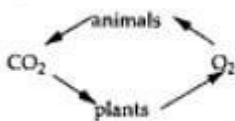
- 1) Where does the food that a plant needs come from?
- A) The plant makes its food from minerals and water.
  - B) The food comes in from the soil through the plant's roots.
  - C) The food comes in from the air through the plant's leaves.
  - D) The food comes in both from the soil and the air.
  - E) The plant makes its food from carbon dioxide and water.**
- 2) Which of the following drawings shows the cycling of carbon dioxide and oxygen in nature?



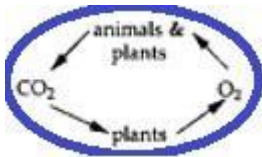
A)



B)



C)



D)

- 3) Which of the following comparisons between the process of photosynthesis and respiration is correct?

**A) Photosynthesis takes place in green plants in the presence of light energy, and respiration takes place in all plants and animals at all times.**

- B) Photosynthesis takes place in green plants only, and respiration takes place in animals only.
- C) Photosynthesis takes place in green plants the presence of light energy, and respiration takes place in all plants, only when there is no light energy, and all the time in animals.
- D) Photosynthesis takes place in all plants, and respiration takes place in animals only.
- E) Respiration in animals is the same as photosynthesis in plants
- 4) Respiration in plants takes place in
- A) In the cells of the leaves only, because only leaves have special pores to exchange gas
- B) In the cells of the leaves only, because only cells that photosynthesize can respire
- C) In every plant cell, because all cells have pores to exchange gas.
- D) In every plant cell, because all living cells need energy to live**
- E) The cells of the roots only, because only roots need energy to absorb water
- 5) In the presence of sunlight, what gas is given off in the largest amounts by green plants?
- A) Oxygen, because plants only photosynthesize and don't respire in the presence of light energy.
- B) Oxygen, because it is a byproduct given off by plants when respiring.
- C) Oxygen, because it is a byproduct given off by plants when photosynthesizing**
- D) Carbon Dioxide, because plants only photosynthesize and don't respire in the presence of light energy.
- 6) Which gas is taken by green plants in large amounts when there is no light energy at all?
- A) Oxygen, because this gas is used in respiration which only occurs in green plants when there is no light energy to photosynthesize.
- B) Oxygen, because this gas is used in respiration which takes place continuously in green plants.**
- C) Carbon dioxide, because it is used in respiration, which takes place continuously in green plants.
- D) Carbon dioxide, because it is used in photosynthesis in the presence of light energy.
- 7) Each spring, farmers plant about 5-10 kg of seed corn per acre for commercial corn production. By the fall, this same acre of corn will yield approximately 4-5 metric tons of harvested corn. Which of the following processes contributes the most to this huge increase in biomass?
- A) Absorption of organic substances from the soil via the roots.
- B) Absorption of mineral substances from the soil via the roots.
- C) Absorption of solar radiation into green leaves
- D) Incorporation of carbon dioxide from the atmosphere into molecules by green leaves**
- E) Incorporation of H<sub>2</sub>O from the soil into molecules by green leaves



Results: 1.48g

3.28g

1.17g

The following question is based on this experiment: Three batches of radish seeds, each with a starting weight of 1.5g (dry), were placed in petri dishes and provided only with light or water or both, as shown in the photo. After 1 week, the material in each dish was dried and weighed. The results are shown below each petri dish.

8) Which of the following processes contributed the most to the increased biomass of the "Light, Water" treatment?

- A) Absorption of mineral substances from the soil via the roots
- B) Absorption of organic substances from the soil via the roots
- C) Incorporation of carbon dioxide gas from the atmosphere by green leaves**
- D) Incorporation of water from the soil into molecules by green leaves
- E) Absorption of solar radiation by green leaves

9) Where did the mass go that was lost by the seedlings in the "No light, Water" treatment?

- A) It was converted to heat and then released.
- B) It was converted into ATP molecules.
- C) It was converted to carbon dioxide and water and then released.**
- D) It was eliminated from the roots as waste material.
- E) It was converted to starch.

10) A basil plant has been absorbing sunlight in window for several days. I then put the plant in a dark closet for the next few days and kept it watered. What will happen to the weight of the plant after having it in the closet?

- A) It will weigh the same since no biomass is produced
- B) It will weigh less because no photosynthesis is occurring.
- C) It will weigh less because it is still respiring**
- D) It will weigh more because the Calvin cycle reactions continue.
- E) It will weigh more because it still has access to water and soil nutrients

11) A potted geranium plant sits in a windowsill absorbing sunlight. How does a root cell (which is not exposed to light) obtain energy in order to perform cellular work such as active transport across its membrane?

- A) ATP is made in the leaves via photosynthesis and moved to the root.
- B) Sugar is made in the root via photosynthesis.
- C) Sugar is made in the leaves via photosynthesis and moved to the root.**
- D) The root cell makes sugar using the dark reactions (Calvin cycle) of photosynthesis.
- E) The root cell makes ATP by photosynthesis and cellular respiration

- 12) Which of the following best describes how a plant cell gets the energy it needs for cellular processes?
- A) Solar radiation provides the energy needed for metabolic processes in cells.
  - B) The chloroplasts provide all the ATP needed by the plants.
  - C) In the light, the ATP comes from the chloroplasts, in the dark, from mitochondria.
  - D) Most ATP comes from digestion of organic matter absorbed by roots, some comes from chloroplasts.
  - E) The sugars produced in photosynthesis can be broken down during respiration to make ATP.**
- 13) Which of the following is the most accurate statement about respiration in green plants?
- A) It is a chemical process by which plants manufacture food from water and carbon dioxide.
  - B) It is a chemical process in which energy stored in food is released using oxygen.**
  - C) It is the exchange of carbon dioxide and oxygen gases through plant stomates.
  - D) It is a process that doesn't take place in green plants when photosynthesis is taking place.
  - E) It is a process that only takes place in the presence of light energy.
- 14) Euglena are single-celled, photosynthetic eukaryotes. How do Euglena obtain energy to do such cellular work such as active transport across membranes?
- A) They transport ATP from the chloroplasts.
  - B) They utilize inorganic nutrients from the surrounding water to make ATP.
  - C) They use sugars made in the chloroplasts to make ATP.**
  - D) They use the ATP made during photosynthesis.
  - E) They utilize organic molecules from their surroundings.
- 15) Which of the following choices about the respiration in plants and animals is true?
- A) Respiration in plants is photosynthesis.
  - B) Plants respire only at night, animals respire all the time.
  - C) Respiration in plants and animals is similar.**
  - D) Plants make anaerobic (without oxygen) respiration, animals make aerobic (with oxygen) respiration.
  - E) While respiration in plants occurs in leaf cells, in animals, it occurs in lung cells.
- 16) 20 small circular pieces, whose diameter is 1 mm, were cut from the leaves which have similar properties from a geranium plant at three different times. Firstly it was cut at 04:00 am (group A), secondly it was cut at 04:00 pm in the same day (Group B), and last one was at 04:00 am in the next day (Group C). Then, the pieces are dried (dehydrate) at 105 °C and weighted. Which of the following results can be obtained?
- A) Group A has the most dried weight
  - B) Group B has the most dried weight.**
  - C) Group C has the most dried weight.
  - D) Group B has the least dried weight.

- E) Groups A and C have the same dried weight.
- 17) Which of the following is TRUE about the sugar molecules in plants?
- The sugar molecules come from the soil.
  - The sugar molecules are one of many sources of food for plants.
  - The sugar molecules are made from molecules of water and minerals.
  - The sugar molecules are made of carbon atoms linked to other carbon atoms.**
- 18) Which of the following is food for a plant?
- Sugars that a plant makes**
  - Minerals that a plant takes in from the soil
  - Water that a plant takes in through its roots
  - Carbon dioxide that a plant takes in through its leaves
- 19) The most important benefit to green plants when they photosynthesize is
- The removal of carbon dioxide from the air through the leaves stomates.
  - The conversion of light energy to chemical energy.
  - The production of energy for plant growth**
  - The production of oxygen into the atmosphere
- 20) Which of the following is true about photosynthesis and respiration in plants?
- Photosynthesis takes place in the leaves, and those leaf cells respire.
  - Photosynthesis takes place in the green parts of the plant, and the leaf cells respire
  - Photosynthesis takes place in the leaves, and every plant cell respire**
  - Photosynthesis takes place in the whole plant, and the leaf cells respire
  - Photosynthesis takes place in the green parts of the plant, and every plant cell respire
- 21) Which of the following statements accurately describes the relationship between photosynthesis and cellular respiration?
- \*Upon further analysis, both B and D were graded as correct answers.
- Photosynthesis occurs only in autotrophs; cellular respiration occurs only in heterotrophs.
  - Photosynthesis uses solar energy to convert inorganics to energy-rich organics; respiration breaks down energy-rich organics to synthesize ATP.**
  - Photosynthesis involves the oxidation of glucose; respiration involves the reduction of CO<sub>2</sub>.
  - The primary function of photosynthesis is to use solar energy to synthesize ATP; the primary function of cellular respiration is to break down ATP and release energy.**
  - Photosynthesis and cellular respiration occur in separate, specialized organelles; the two processes cannot occur in the same cell at the same time
- 22) Which of the following equations best represents the process of respiration in plants?
- A. **Glucose + oxygen       $\longrightarrow$       energy + carbon dioxide + water.**



B. Carbon dioxide + water  $\longrightarrow$  energy + glucose + oxygen.

C. Carbon dioxide + water  $\xrightarrow[\text{Chlorophyll}]{\text{light energy}}$  oxygen + glucose.

D. Glucose + oxygen  $\longrightarrow$  carbon dioxide + water.

23) Which of the following equations best represents the overall process of photosynthesis?

A. Glucose + oxygen  $\xrightarrow[\text{light energy}]{\text{chlorophyll}}$  carbon dioxide + water

**B. Carbon dioxide + water  $\xrightarrow[\text{light energy}]{\text{chlorophyll}}$  glucose + oxygen**

C. Carbon dioxide + water + energy  $\longrightarrow$  glucose + oxygen

D. Oxygen + water  $\xrightarrow[\text{light energy}]{\text{chlorophyll}}$  glucose + carbon dioxide

24) Which of the following statements is TRUE about the carbon dioxide that is used by plants?

A) It is combined with oxygen to make sugar molecules.

B) It is absorbed through the roots of plants.

**C) It comes from the air.**

D) It is food for plants.