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Self-Explaining Photosynthesis to Achieve Conceptual Change: An Analysis of Explanation Content

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Abstract. Students enter biology coursework with various misconceptions needing revision. However, achieving conceptual change of these misconceptions in the classroom is notoriously difficult and requires specific instruction. Self-explanations can promote conceptual change, but their effects can depend on the content produced. This study investigates how the content of learners' explanations of photosynthesis processes affects learning. We examined data from an online assignment in introductory biology where 118 college undergraduates answered multiple-choice questions related to commonly misconceived processes in photosynthesis and respiration and were then prompted to self-explain the correct answer. One week later, students took a test that measured learning in the activity. Using mixed methods analyses, we qualitatively explored the types of explanations learners made, categorized the different types of explanations, and performed quantitative analyses to examine relations between explanation content and test scores. We identified five categories of self-explanations that varied in engagement, accuracy, and focus. Accuracy of the explanation mattered; accurate explanations predicted higher test scores, and inaccurate explanations predicted lower test scores. We also identified three different groups of learners: highly performing learners who were actively engaged and accurate; moderately performing learners who were engaged but often paraphrased or explained inaccurately; and low performing learners who were disengaged and avoided explaining. We provide implications for use of self-explaining misconceived material.

Keywords: self-explanation; misconception; conceptual change; mixed-method; biology

1. Introduction

At the college level, introductory biology courses serve a wide range of students, with varying abilities, interests, and background knowledge. The content delivered in these courses typically assumes students are equipped with high school-level biology understanding. Yet, despite K-12 instruction in biology, college students bring and maintain inaccurate knowledge and misconceptions about core concepts (Gregory, 2009; Heddy & Sinatra, 2013; Meir et al., 2007; Oliver et al., 2018). Correcting these misconceptions requires conceptual change of the prior knowledge, and this is both a difficult and necessary task for science educators (Sinatra & Taasoobshirazi, 2011; Vosniadou, 2007). Conceptual change is a complex process of knowledge revision that typically does not occur spontaneously, and instruction must be tailored to facilitate this process when needed (Nadelson et al., 2018). Refutation texts can be effective at inducing conceptual change in the classroom (Sinatra & Broughton, 2011; Tippet, 2010), but self-explanation prompts may be a more effective strategy in actively engaging students in this process online (Oliver et al., 2018).

In this study, we explore the use of self-explanations to promote conceptual change in an online activity covering commonly misconceived content on photosynthesis and respiration. While self-explanations are generally a recommended practice and can be effective at promoting conceptual change, characteristics of the explanation produced, like the accuracy and engagement (Chi, 2018; Rittle-Johnson & Loehr, 2017), can mediate the effectiveness of the strategy. Understanding the role of explanation accuracy is particularly important in scenarios where the content being learned is already highly misconceived and inaccurate explanations are likely. We investigated undergraduate biology students who held misconceptions about photosynthesis and respiration (Oliver et al., 2018) and assessed what types of explanations students produced about this material and how different types of explanations affected learning. To accomplish this, we designed an activity to activate existing misconceptions using questions with misconceptions embedded as answer options. We then provided students with correct answer feedback, prompted them to self-explain the correct answer provided, and measured learning one week later with a test covering information from the activity.

To assess what types of explanations students were producing and how each type related to learning, we first identified features of learners' explanations through an exploratory qualitative analysis of explanation content. We then coded those features and used them to predict performance on the test. We addressed two research questions with this mixed methods analysis:
RQ1: What types of self-explanations do learners provide of commonly misconceived biology content?
RQ2: How do different types of self-explanations relate to test performance?

We hypothesized that students would produce explanations that varied in accuracy and engagement, with inaccurate explanations being common. We further hypothesized that accurate explanations would predict increased test performance, but inaccurate explanations would predict decreased test performance. Our research questions and hypotheses draw from literature on conceptual change, biology misconceptions, and self-explanations, and our results have direct implications for the design of online self-explanation tasks in introductory biology courses.

2. Review of Literature

2.1 Conceptual Change

Knowledge building is most often associated with learning, where new information is added to existing knowledge. A different type of learning is associated with knowledge correction and is referred to as conceptual change (Sinatra, 2005). The process of conceptual change is necessary when a learner has a misconception, which can be a hindrance to further learning if left unrevised (Nadelson et al., 2018; Sinatra & Pintrich, 2003). A misconception is defined as inaccurate prior knowledge that conflicts with the knowledge currently accepted by experts (Tippet, 2010), and it could involve incorrect knowledge of various types and scopes (Chi, 2013; Vaughn et al., 2020). Learners cannot simply replace or delete misconceptions from their knowledge structures, and conceptual change involves a complex learning process that typically must affect the use of multiple types and layers of knowledge (Vaughn et al., 2020). Modern models of conceptual change vary slightly based on whether they describe processes of permanent knowledge restructuring and shift (Chi, 2008; Vosniadou, 2007) or the addition of new knowledge paired with the inhibition of relatively unchanged erroneous knowledge (Kendeou & Van Den Broek, 2007; Vaughn et al., 2020).

While theories surrounding the nature of conceptual change vary according to ideas about how the new information is situated in knowledge structures and what happens to the old information, researchers agree that the process of change must begin with the learner recognizing that their knowledge conflicts with the information they are learning, believing in the accuracy of the new knowledge, realizing a need to change their existing knowledge, and being willing to do so (Kendeou & van den Broek, 2007; Nadelson et al., 2018; Vaughn et al., 2020; Vosniadou, 2007). As such, instruction must be specifically tailored to guide students through these processes when conceptual change is necessary.

2.2 Biology Misconceptions

In science domains, misconceptions are common because students have their own personal, but naive and often misconceived theories to explain natural phenomena (Chi, 2005; Guzzetti, 2000; Sinatra & Taasoobshirazi, 2011; Vosniadou, 2007). As such, an inherent part of learning science is encountering information in the classroom that conflicts with one's pre-exiting ideas (Sinatra & Chinn, 2012). While conceptual change is an important goal for all science educators, this study focused on misconceptions found in introductory biology students, namely misconceptions related to photosynthesis and respiration. These topics involve a number of interrelated and sometimes abstract concepts, which can make these biological processes some of the most difficult for students to correctly understand no matter their age (Galvin et al., 2015; Svandova, 2014). Despite years of prior formal instruction, undergraduate college students and pre-service science teachers still maintain misconceptions about these processes (Galvin et al., 2015; Karakaya et al., 2021; Oliver et al., 2018; Södervik et al., 2015).

Research has documented a number of common misconceptions regarding photosynthesis and respiration, including the incorrect beliefs that: plants get their food to grow through their roots; plants do not respire; plants respirating is similar to breathing in animals; and respiration only takes places when photosynthesis does not (AAAS, 2016; Galvin et al., 2015; Oliver et al., 2018). Students learn the correct explanations for these processes in class, but they do not undergo conceptual change of their related misconceptions and sufficiently incorporate the correct information into their conceptual knowledge (Tas et al., 2012). As a result, these misconceptions often persist after instruction. This poses a significant problem in biology education because correctly understanding the broader concepts of plant nutrition and ecology relies on the correct understanding of photosynthesis and respiration (Kohn et al., 2018). Instruction must be tailored to guide students through the revision of these misconceptions, and this can be particularly challenging in college-level introductory biology courses that must serve class sections with large enrollments of students with varying abilities, interests, and background knowledge. Add in the increased need and demand for online instructional environments, and you are left with a critical need for conceptual change instruction strategies that can serve a wide population of students in an online format.

Refutation texts, which identify common misconceptions and usually directly refute them, are a common instructional strategy for prompting conceptual change (Sinatra & Broughton, 2011; Tippet, 2010). However, they may not be as effective as self-explanation tasks, at least in online biology education environments, where passive activities like reading text may not sufficiently engage students in conceptual change processes (Oliver et al., 2018). Previous work with introductory biology students indicated that adding in short refutation texts as retrieval practice feedback activity did not promote conceptual change but adding in prompts to self-explain correct answer feedback did (Oliver et al., 2018). Thus, self-explaining appears to be a useful tool for engaging students in the conceptual change online.

2.3 Self explanations

Prompting students to produce explanations of content, referred to as self-explanations, is an effective instructional strategy across ages and disciplines (Bisra et al., 2018; Fonseca & Chi, 2011; Renkl, 2014; Rittle-Johnson & Loehr, 2017; Roy & Chi, 2005). Self-explanations are a generative learning activity that can facilitate learning by encouraging the learner to construct new information or manipulate presented information (Fiorella & Mayer, 2016). Self-explaining can also promote the integration of incoming and prior knowledge (Fiorella & Mayer, 2016; Fonseca & Chi, 2011; Lombrozo, 2006).

The instructional means used to prompt self-explaining vary. Sometimes, learners are given instructions to read text and then explain it (e.g., Chi, 2000). Other times, learners are instructed to provide an explanation of each step while solving a problem (e.g., Aleven & Koedinger, 2002), to explain a worked example (e.g., Hausmann & VanLehn, 2007; Renkl, 2014), to provide an explanation for category membership (Williams et al., 2013; Williams & Lombrozo, 2010), or to explain the correct answer to a question (e.g., "Why is X the correct answer?"; Oliver et al., 2018).

Although research and practice have documented the effectiveness of self-explaining, leading to broad recommendations for use (e.g., Common Core, 2022; Dunlosky et al., 2013), there are conditions where self-explaining may not be helpful (Rittle-Johnson & Loehr, 2017). As with any instructional task, interactions between specific task demands, content, and learner characteristics in any given situation may or may not result in the desired learning outcome (Lee & Kalyuga, 2014; Van Merrienboer & Sweller, 2005). The effectiveness of self-explaining can be influenced by a number of factors related to the learner, like prior knowledge and motivation (e.g., Linnenbrink-Garcia et al., 2012; Vosniadou, 2007), academic self-concept (Roelle & Renkl, 2020), or engagement (Chi, 2018). It can also be influenced by task characteristics, like instructions (Bisra et al., 2018) or what material is being covered (Rittle-Johnson & Loehr, 2017).

The content of learners' self-explanations can provide insight into the cognitive processes occurring, or not occurring. Some explanations are better than others because they elicit more germaine learning processes (Sweller, 2010) and produce greater learning gains. High-quality explanations indicate active engagement by the learner and deep-processing of the content being explained (Chi, 2018; Chin & Brown, 2000; Rittle-Johnson & Loehr, 2017). They may include inferences, link new and prior knowledge, and reference key principles relevant to the topic (Roy & Chi, 2005), meaningful connections to the facts, deductive reasoning from given examples, or application of the knowledge to future examples (Renkl, 1997). Conversely, low-quality explanations indicate shallow processing and little engagement from the learner. They may consist of simple paraphrasing or demonstrate avoidance of the task itself (Roy & Chi, 2015). Low-quality explanations are typically produced by learners who are disengaged from the act of self-explaining and employ minimal effort (Kwon & Jonassesn, 2011; Renkl, 1997).

The accuracy of students' self-explanations is an important factor to consider, and it is most helpful for students to produce accurate explanations of information (Chi, 2018; Rittle-Johnson & Loehr, 2017). However, in large introductory biology classes where students hold persistent misconceptions, inaccurate explanations should be expected. In the context of conceptual change, producing an inaccurate explanation may serve to further reinforce students' existing misconceptions and deter learning, or, conversely, maybe the effort associated with producing an inaccurate explanation is still beneficial to learning. Thus, understanding if students are commonly producing inaccurate explanations, and whether those are detrimental to learning, has important implications for instruction. The roles and utility of accurate and inaccurate self-explanations have not yet been investigated in relation to conceptual change in introductory biology classrooms.

In the current study, we aimed to assess what types of explanations students produce when self-explaining misconceived content, with a focus on accuracy, and how different types of explanations related to learning. We assessed this in a population of students, who, according to a previous analysis (Oliver et al., 2018), held persistent misconceptions about photosynthesis and respiration by using a computer-based conceptual change activity that combined retrieval practice with correct answer feedback and self-explanation prompts. Our work responds to calls by biology education and learning science research by providing insight into how naive and immature ideas about phenomena interact with conceptual change intervention (Cordero & Lineback, 2013; Leonard et al., 2014), and also responds to needs for computer-based self-explanation activities (Bisra et al., 2018).

3. Methodology

3.1 Design

This study employed a sequential mixed-methods approach that collected qualitative data in one session and quantitative data in another and further utilized a data-transformation design. This approach is a powerful way to both describe and measure learning in biology education (Warfa, 2017) while capturing the complex representations of knowledge (Chi, 1997) that would be associated with misconceptions and conceptual change. We collected students' typed self-explanations of questions related to photosynthesis and respiration and then measured their performance on an associated test one week later. We then conducted an exploratory qualitative analysis of explanation content to identify categories, quantitized the self-explanation data using the category schema developed, merged the two datasets, and finally used the quantitized explanation categories to predict learning on the test in a quantitative multiple regression analysis.

3.2 Participants

One-hundred and eighteen undergraduate college students (*Mean age* = 21 years) from a large urban Southeastern university participated in this study. Of the 118 participants, 70% were female, 26% were male, and 4% chose not to provide information. Furthermore, 39% reported being African American, 24% Caucasian, 18% Asian/Pacific Islander, 7% Hispanic, 8% other/multiracial, and 4% chose not to provide information. All students enrolled in the nine Introductory Biology II course sections offered during the associated semester were invited to participate in this study. Students must complete and pass Introductory Biology I, which covers photosynthesis and respiration, at this university before taking Introductory Biology II. Traditionally students take Introductory Biology I the semester before taking Introductory Biology II, but this can vary. Students enrolled in the associated classes received course credit for completing activities described here, and students who opted to participate in the study by having their data collected did not receive any additional credit or compensation.

3.3 Materials

3.3.1 Prior knowledge assessment

We compiled a short 15-item multiple-choice assessment to generally measure relevant domain knowledge from participants' prior Introductory Biology I course. The multiple-choice questions were acquired from the *Capturing Solar Energy: Photosynthesis* chapter of an introductory biology textbook test bank (Audesirk et al., 2013). To support ecological validity of the items selected, we asked biology instructors to select questions covered in the previous Introductory

Biology I course, and these items were moderately reliable in this sample (α = .61). Of note, none of the questions from the prior knowledge assessment were used in the revision activity or test described below. The questions did not have misconceptions intentionally designed into the answer choices as lures as did the revision activity and test questions. See *Appendix 1* for questions from the prior knowledge assessment.

3.3.2 Revision Activity

The revision activity aimed to activate, refute, and promote change of common misconceptions relating to photosynthesis and respiration if present. More specifically, the activity was designed to: 1) Activate common misconceptions by asking multiple-choice questions and embedding the misconceptions as potential answer options; 2) Refute the misconceptions (if present) by providing immediate correct answer feedback; and 3) Promote learning by prompting students to self-explain the correct answer feedback. This activity was a learning tool comprised of 12 multiple-choice questions selected from previously validated measures of respiration and photosynthesis misconceptions (AAAS 2061, 2016; Amir & Tamir, 1994; Boomer & Latham, 2011; Galvin et al., 2015; Haslam & Treagust, 1987). Questions that targeted the common misconceptions identified in this population were selected and adapted for activity formatting only; the question content did not change from the original sources.

Throughout the revision activity, the following misconceptions were expressed as answer options in a number of ways: when plants photosynthesize, they do not respire (Haslam & Treagust, 1987; Galvin et al., 2015; Svandova, 2014); plants do not respire (Amir & Tamir, 1994); plants are able to grow because of food they get from the soil (AAAS 2016, 2016; Galvin et al., 2015; Svandova, 2014); and respiration in plants is tantamount with breathing in animals (Anderson et al., 1990; Galvin et al., 2015). Each misconception was included as an answer choice in multiple activity questions to provide numerous opportunities for activation of the misconception and potential revision. A combination of knowledge and application questions were both included in the revision activity. Application questions asked participants to apply their knowledge to answer questions about a specific scenario (e.g., in the experiment shown above, what happened to the mass lost in the 'water, no light' treatment?). Knowledge questions asked participants to accurately identify basic concepts or facts (e.g., which of the following about respiration is true?). Every multiple-choice question had at least one misconception embedded in the four or five answer choices. More than one misconception was included in some of the question answer choices. See *Appendix 2* for activity questions.

3.3.3 Test

To measure the learning from the revision activity one week later, a 24-item multiple-choice test was utilized. Included in the test were 12 new near-transfer questions and the 12 original questions from the activity. Like the original activity questions, the 12 new near-transfer questions included both knowledge and application questions. The near-transfer knowledge questions covered the same content, just asked in a different way. The near-transfer application questions maintained the same structure as the original activity questions, but varied the scenarios provided. Reliability for the test was adequate (24 items; α = .71). See *Appendix 3* for test questions.

3.4 Procedure

Participants completed two separate online sessions, one week apart, conducted through Qualtrics Online Survey Software. Session one included a prior knowledge assessment and revision activity and took approximately 30 minutes to complete (*SD* = 11 minutes). Session two included the test and took approximately 20 minutes to complete. Both sessions were assigned at the beginning of the semester as online homework activities. Participants completed the assessments either at home or in class from a computer. Instructors provided the link to each of the sessions one week apart to ensure the one-week delay between the first and second sessions. Qualtrics Survey Software also sent each participant reminder emails for the second session with the link exactly one week after completing the first activity.

3.4.1 Session 1

Once entered into the Qualtrics survey using the link provided from their instructor, participants were directed to first complete an informed consent and then routed to the assessment on prior knowledge. Before starting the assessment, participants received the following instructions: "We are interested in how much you 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. Please do not look up the answers. If you do not know an answer, try to select the best option you can."

After completing the prior knowledge assessment, the survey routed participants to the revision activity. The revision activity presented questions in a randomized order. The procedure for each individual question spanned across two Qualtrics pages. On the first page, participants were prompted to read the question and select the best answer. After selecting their answer, the survey routed participants to a new page that presented the question again with correct answer feedback (i.e., correct answer highlighted and pointed out in the question). Directly below the correct answer feedback, participants were provided with a text box and 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. After completing a question, participants were routed to the next question and the activity continued like this for all 12 questions. After completing all 12 revision activity questions, participants were prompted to provide information to receive credit. Credit was based on completion.

3.4.2 Session 2

The following week, instructors and Qualtrics Survey Software both provided participants with the link to the second session. Upon entering the survey for the test, participants were informed we would be assessing their learning from the activity the week prior and were then presented with test questions. Each question was presented on a separate page and in randomized order, but without correct answer feedback. After answering all 24 test questions, participants answered demographic questions and read a debriefing statement.

4. Analyses and Results

Participants' data from session 1 and session 2 were downloaded from Qualtrics Survey Software, linked together using IDs, and subsequently deidentified. Participants who had not completed both sessions were dropped from analysis. We conducted a qualitative analysis of explanation data, which included 12 typed self-explanations for each student, to answer our first research question that asked what types of explanations participants provided. We then qualitized the self-explanation data by assigning each explanation with a code according to the category schema developed. We subsequently computed counts for how many of each explanation type participants produced. These explanation-category variables were used in a quantitative regression analysis to answer our second research question that asked how different types of explanations related to learning. Both the qualitative analysis with results (RQ1) and the quantitative analysis with results (RQ2) are described below.

4.1 Research Question 1: What Types of Self-Explanations Do Learners Provide of Commonly Misconceived Biology Content?

4.1.1 Qualitative Analysis and Category Development

Using a method outlined in Chi (1997) for exploring and coding verbal data, we developed a formal coding scheme to categorize the types of explanations students were producing through four rounds of collaborative and reiterative qualitative analysis across three researchers. The generation of categories was an entirely bottom-up process with the exception of two aims: 1) identify inaccurate explanations and 2) create mutually exclusive category descriptions to be used for predictive quantitative analysis. Each round of this process involved short coding assignments, collaborative reflection on the process, and reiteration of the coding scheme. In the first round of coding, raters examined the verbal data provided by the participants to identify trends and possible categories for explanations. Based on various trends observed in the data, seven initial categories were created: *off-task*, *shallow*, *paraphrase*, *explains accurately*, *explains inaccurately*, and *reflection of knowledge*. Each category was defined and assigned concrete examples. Explanations for activity question 10 were unable to be worked into a coding scheme or understood, likely because of the low reliability of this question, as was indicated by a low reliability coefficient across participants (Cronbach's alpha; $\alpha = .5$). As a result, in this round of analysis, question 10 explanations were dropped from qualitative and quantitative analysis. The associated question on the test was also dropped.

During the second round of coding, it became necessary to provide specific instructions for coding categories across particular questions. For instance, the answer choices to activity question two were all diagrams of the carbon cycle, and raters had to determine what qualified as paraphrasing of the information illustrated in the diagram. These determinations were then included as instructions for coding. The categories were given a numeric designation for coding and another round of coding was conducted with the codebook to assess reliability.

During the third round of coding, raters further defined the categories with more detailed descriptions based on the different types of explanations raters found in each question. The raters discussed each question individually to identify any confusion and develop explicit rules where needed. Ultimately, discussions led to the creation of specific coding instructions for questions 2, 3, 7, and 11. In addition, the categories off-task and shallow were combined into an avoidance category due to the explanations provided being similar in style and engagement, with explanations such as "I don't know" being combined with avoidance (e.g., "sfjndfa") and incomplete responses (e.g., "the plant"). An uncodeable category was also added because a few explanations were difficult to interpret or understand.

Finally, raters applied the coding scheme detailing the final six categories to a randomly selected group of 35 participants' explanations. Interrater reliability (IRR) was determined for explanations within each activity question as indicated by Cronbach's alpha. Initial IRRs for category assignment in each question were .80 or greater. The final codebook consisted of six mutually exclusive categories: avoidance, paraphrase, explains accurately, explains inaccurately, reflection of knowledge, and uncodeable. The codebook is located in Appendix 4.

Using the finalized categories, each rater coded explanations for three to four activity questions in SPSS 24. Each explanation was assigned to a single category, a mutual exclusivity made possible by the category definitions and instructions developed. We chose to use mutually exclusive categories in which only one code was assigned to each explanation with our quantitative analysis and research questions in mind.

4.1.2 Qualitative Analysis Results
Our qualitative analysis indicated six categories of explanations during the revision task.

Avoidance. The avoidance category was composed of responses that did not include explanations of content. These types of responses were seen in learners who were disengaged from the task, did not complete the task as instructed, or commented they "don't know." Responses demonstrating disengagement from the task included responses where the learner randomly filled in the textbox with letters and characters (e.g., "kdjfnv"), made comments irrelevant to the task (e.g., "I like food"), or made grossly incomplete explanations (e.g., "the plant lives"). Responses demonstrating the learner did not follow the instructions—which were to explain the correct answer indicated—typically included comments on whether the learner initially got the answer correct (e.g., "Heck yea! I was right"), or incorrect ("got it wrong"). Responses only indicating the learner did not know (e.g., "idk/I don't know/I'm not sure") were also common in this category. Some "I don't know"-type responses may have demonstrated the learner did not have enough prior knowledge to attempt to explain the answer and others may have demonstrated another way for learners to disengage and simply fill in the textbox.

In some cases, responses in the avoidance category included some combination of these features (e.g., "I don't know I got it wrong"). In all cases, explanations in the avoidance category lacked any mention of relevant content or lacked a complete thought. Thus, if a learner stated they did not know or explained how they chose the answer but then also further explained by introducing additional information (e.g., "I'm not sure, I thought that light energy and c02 were correlated"), it would not fall into this category since content, whether accurate or inaccurate, was introduced.

Uncodeable. The uncodeable category contained responses that demonstrated some attempt to explain (i.e., they did not demonstrate avoidance) but were incoherent and unable to be understood enough to reliably categorize or determine accuracy. Explanations were uncodeable because they were either incoherently written (e.g., "Carbon dioxide earths dinner need to surevhvr ") and/or were hard to pull meaning from (e.g., "oxygen and sunlight give off each other"). These explanations were rare, with only a few uncodeable explanations occurring within each question and not necessarily within the same learners. That is, no learners consistently provided uncodeable explanations across questions.

Paraphrase. The paraphrase category included explanations that only summarized or restated parts of the question and/or answer without adding any additional information from prior knowledge. Paraphrased explanations included responses that restated part of the question or answer verbatim or that simplified part of the question or answer into lay terms. For instance, the explanation "Plants give off oxygen during photosynthesis" was considered a paraphrase of the correct answer "Oxygen, because it is a byproduct given off by plants when photosynthesizing" because it restates content from the answer without incorporating any novel terms or additional information not presented in the question or answers.

Paraphrased explanations were common and demonstrated relatively low levels of engagement in the task because they lacked the "why" aspect intended by the explanation prompt; that is, they only restated the correct answer in some way without elaborating to explain why the answer was correct. Paraphrased interpretations of the information had to be accurate statements to be considered in this category. From a cognitive perspective, while paraphrased responses demonstrate the rehearsal of accurate information, they did not demonstrate the learner was engaging any conceptual change processes by monitoring the accuracy of their prior knowledge, since no prior knowledge was introduced.

Accurate. The accurate category included explanations that added additional, correct information not included in the question and/or answers. Accurate explanations ranged from paraphrased responses that incorporated technical terms not present in the question/answers to responses that explicitly explained why the indicated answer was correct using additional information from prior knowledge. For instance, accurate explanations of the correct answer "The plant makes its food from carbon dioxide and water" ranged from paraphrases correctly applying unmentioned terms (e.g., "In photosynthesis, *the energy* is acquired from carbon dioxide and water") to explanations that added additional information to explain why the answer was correct (e.g., "Plants are autotrophs which mean they make their own food through the usage of CO2 and water in photosynthesis"), and sometimes included explanations that made accurate comments about the other, incorrect, answer choices (e.g., "It's the two requirements for a plant to live. Mineral rich soil would aid but it isn't absolutely required"). Thus, the main difference between paraphrased and accurate explanations was the incorporation of additional, correct information or technical terms in accurate explanations.

Inaccurate. The inaccurate category included explanations that explicitly stated any level of incorrect information. The levels of inaccuracy varied widely in this category. Inaccurate explanations could range from the incorrect usage of a term, to the statement of an incorrect fact, to the application of multiple pieces of inaccurate information. Most inaccurate explanations demonstrated the incorporation of incorrect prior knowledge. Others demonstrated inaccurate paraphrases where the learner tried to paraphrase but misinterpreted what the answer said. In all cases, inaccurate explanations included the rehearsal or application of incorrect knowledge and demonstrated misunderstandings (i.e., they lacked sufficient prior knowledge to understand the correct information enough to accurately explain, but attempted to explain anyway) or misconceptions (i.e., the information was interpreted using inaccurate prior knowledge and resulted in a misconceived explanation). For instance, for the question "Which of the following is the most accurate statement about respiration in green plants?" that had the correct answer "It is a chemical process in which energy stored in food is released using oxygen," the following explanations were considered inaccurate:
Example 1: Plants prefer photosynthesis but can perform respiration as well. Respiration is more so a last resort effort"

Example 2: "Energy is needed to provide the plant with fuel to grow. Food for plants is absorbed through the roots in the ground."

Example 3: "Respiration is just an old change of gases."
The first example demonstrates the application of incorrect prior knowledge that was not necessarily related to any of the common misconceptions identified in previous research.

Examples 2 and 3 demonstrate the application of common misconceptions in the explanations, namely the misconception that food/energy is absorbed through the roots and the misconception that respiration is the same as breathing. Even if explanations contained features of other categories (e.g., it also included a statement of correct information or indications that they "did not know") in addition to any level of explicit inaccuracy, they were categorized as inaccurate. In this way, we applied a hierarchy of coding to ensure mutual exclusivity for the analysis that follows.

Reflection of Knowledge. Explanations in this category demonstrated the learner was remembering the source of their knowledge, monitoring their confidence in the accuracy of their prior knowledge, or acknowledging a conflict between their knowledge and the information presented. In responses where the learners recalled the source of their knowledge, the explanations spoke directly about how the learners came to have certain knowledge. These explanations typically involved comments indicating the answer was correct because they learned the information in the answer from a credible source (e.g., "If I can remember correctly, last semester we did a respiration lab where it showed that seedling uses respiration. All plants uses photosynthesis because that is how they get their food"), and at times that credible source was a previous activity question (e.g., "The last question just said that respiration is always taking place so the answer could not have been D").

In responses where the learners correctly acknowledged a conflict between their prior knowledge and the information presented, learners pointed out what they previously thought was different from the correct answer and oftentimes went on to acknowledge their prior knowledge was inaccurate. Sometimes this included the learner simply comparing their incorrect prior knowledge with the information presented in the question (e.g., "I thought plants absorbed CO2, not oxygen"). Other times it included the learner explicitly pointing out their prior thinking was misconceived and acknowledging the correct information (e.g., "I put C because I wasn't thinking about how plants output CO2. However, they do. Through the process of photosynthesis, they create a small amount"). However, explanations that introduced the source of inaccurate prior knowledge, but then did not correctly monitor the information as incorrect (e.g., "we learned in lecture last semester that only the leaves of a plant can breathe") would be categorized as inaccurate since the explanation contained the explicit statement of inaccurate information.

The frequency counts for each explanation type are depicted in Figure 1. *Avoidance, paraphrased*, and *accurate* explanations were the most common type of explanation produced. *Inaccurate* explanations were also common. The counts of explanations in the *Reflection of Knowledge* category were relatively low.

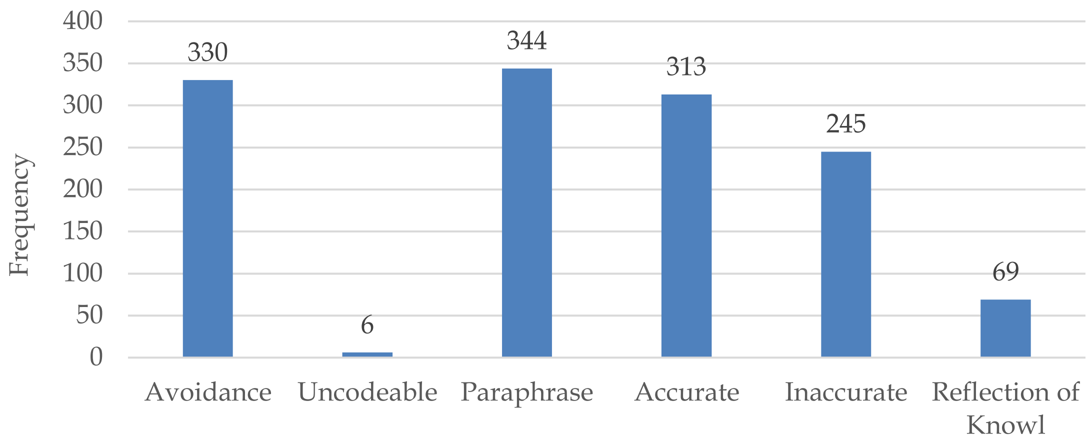

Figure 1. Counts of Explanations Across all Learners and Questions

4.2 Research Question 2: What Types of Explanations Predicted the Highest and Lowest Test Scores?

4.2.1 Quantitative Analysis

To determine how each type of explanation related to learning, we utilized counts of each explanation type within participants (avoidance, paraphrased, accurate, inaccurate, and reflection of knowledge) and prior knowledge scores (i.e., number of items correct) as predictors for test scores in a multiple linear regression model. Initial assumption checking indicated multicollinearity between the avoidance explanations and all other explanation types, and thus avoidance explanations were excluded from the model. The correlation between counts of avoidance explanations and other explanation types occurred as a result of the coding scheme. Since learners were only prompted to generate 11 explanations and categories were mutually exclusive, as the number of paraphrased, accurate, inaccurate, and reflection of knowledge explanations a learner made went up, the number of avoidance explanations automatically went down (and vice versa).

After removing avoidance explanations, multicollinearity was not a concern in the resulting model (all VIF's > 2.0; all tolerance > 0.8). Assumptions for independent errors (Durbin-Watson value = 1.97), normality, and homoscedasticity were also met. Upon meeting assumptions, five predictors of test scores were entered in to a multiple linear regression model predicting test scores: prior knowledge, paraphrased, accurate, inaccurate, and reflection of knowledge. Initial results indicated that prior knowledge scores (p = .10) and reflection of knowledge explanations (p = .51) were not significant predictors nor did they increase model fit, leading to their exclusion from the model. The final model used the number of accurate, inaccurate, and paraphrased explanations each participant produced to predict the percentage of answers they got correct on the test.

4.2.2 Multiple Linear Regression Results

Our final model predicted a significant amount of variance in test scores, $F(3, 117) = 39.63$, $p < .001$, $R^2 = .51$. Specifically, counts of accurate explanations ($\beta = 5.06$, $p > .001$) and inaccurate explanations ($\beta = -2.10$, $p = .01$) were significant predictors of test scores. Paraphrased explanations were marginally significant ($\beta = 0.96$ $p = .08$). The resulting model accounted for 51% of the variability in test scores and is illustrated by the following regression equation:

$$Y = 28.65 + 5.06_{accurate} - 2.10_{inaccurate} + .96_{paraphrase.}$$

Out of 100 test points, each accurate explanation corresponded with a 5-point *increase* on the test; whereas each inaccurate explanation corresponded with a 2-point *decrease* on the test, and each paraphrased explanation corresponded with a one-point *increase* on the test.

4.2.3 Post-Hoc Cluster Analysis

While our model was able to establish the relationship between accurate and inaccurate explanations and test scores, the high frequency of avoidance explanations makes it pertinent from an instructional standpoint to also identify how avoiding the task (i.e., not attempting to explain) plays a role. This analysis was motivated post-hoc since the avoidance category had to be removed from the regression model due to multicollinearity. We conducted a two-step cluster analysis to identify if and how learners clustered into different groups based on their levels of prior knowledge, counts of explanation types (including avoidance), and test performance. A two-step cluster analysis is used to identify learner profiles that may not be apparent in predictive models (Yu, 2010). It is exploratory in nature and useful for identifying groups of people based of cognitive or behavioral variables (Benassi et al., 2020).

Initial cluster analysis indicated that the reflection of knowledge category was not a significant input, and it was dropped from the final cluster analysis to increase the analysis's measure of cohesion and separation. We included the following six inputs into a final two-step analysis in SPSS 24: test (percentage correct), prior knowledge (percentage correct), number of accurate explanations, number of inaccurate explanations, number of paraphrased explanations, and number of avoidance explanations. The two-step cluster analysis resulted in three clusters of learners that were characterized by natural cohesion of patterns in the six inputs (cluster quality = 0.6). We conducted a series of one-way analyses of variance (ANOVA) comparing means for each input across the 3 clusters to validate the clusters identified. ANOVA results indicated significant differences across clusters for all inputs, supporting the validity of the cluster analysis. Tukey HSD post-hoc tests on pairwise comparisons indicated significant differences across all 3 clusters (p's < .05) for all inputs except paraphrased explanations, in which the means for the high and low performing groups were not significantly different (p = .12). Results for these confirmatory ANOVA's are displayed in Table 1.

Table 1. Cluster Analysis Validity – ANOVA Results

Input		*Sum*	*df*	*Mean Square*	*F*	*Sig.*
Test	Between	1173.09	2	586.54	49.03	.000
	Within	1375.73	115	11.96		
	Total	2548.62	117			
Prior Knowl	Between	46.73	2	23.36	5.81	.004
	Within	461.74	115	4.01		
	Total	508.48	117			
Accurate	Between	573.77	2	286.88	117.41	.000
	Within	280.98	115	2.44		
	Total	854.75	117			
Inaccurate	Between	97.11	2	44.55	26.86	.000
	Within	207.88	115	1.80		
	Total	304.99	117			
Paraphrased	Between	281.11	2	140.55	38.67	.000
	Within	418.04	115	3.63		
	Total	699.15	117			
Avoidance	Between	950.01	2	475.01	209.10	.000
	Within	261.24	115	2.27		
	Total	1211.25	117			

Once the cohesion and separation were confirmed, we examined how each of the inputs contributed to the formation of clusters. Results from the two-step cluster analysis indicated the importance of each variable using a Relative Importance

Index, which identifies the variable that contributed the most to clustering cohesive groups and relates the other inputs to it. The relative importance of each input is seen in Figure 2.

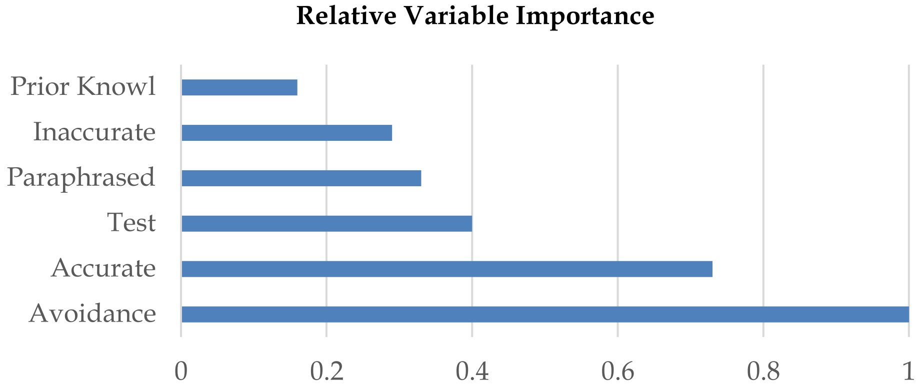

Figure 2: Relative Importance of Each Input in the Two-Step Cluster Analysis

The number of avoidance explanations each participant had was the most important factor when clustering them into groups. Relative to the number of avoidance explanations, the number of accurate explanations and performance on the test were the next two most important predictors. Interestingly, prior knowledge was not a particularly important input for clustering participants. Since test scores were significantly different across the three clusters, we opted to conceptualize and label the clusters according to their test performance. That is, we labeled the clusters according to whether that cluster had the highest (high performing), second highest (moderately performing) or lowest (low performing) average test score. For each cluster, the average percentage correct on the test, average percentage correct on the prior knowledge assessment, and average number of accurate, inaccurate, paraphrased, and avoidance explanations can be seen in Table 2 below.

Table 2. Means for Inputs (i.e., Learner Characteristics) Across Clusters

Learner Characteristics	Means High Performing	Moderate Performing	Low Performing
Test	71%	40%	32%
Prior Knowl.	62%	45%	40%
Accurate	8.5	2.85	1.15
Inaccurate	0.78	2.76	1.12
Paraphrased	1.39	4.04	1.45
Avoidance	0.33	1.34	7.27
N	21	58	39
%	18%	49%	33%

As seen in Table 2, the high performing group was the smallest cluster (*n*=21) with an average test score of 71%; the moderate performing group was the largest cluster (*n*=58) with an average test score of 40%; and the low performing group was the second largest cluster (*n* = 39) with an average test score of 32%. Prior knowledge varied across each cluster in predictable fashion and aligned with test performance. However, differences in prior knowledge were small, and overall levels of prior knowledge were relatively low for all clusters, with the highest performing cluster averaging only 41%. Thus, these clusters were not characterized by large differences in incoming prior knowledge, which is likely why prior knowledge was the least important input, as indicated by the relative importance illustrated in Figure 2.

The difference in inaccurate explanation counts across the three clusters was statistically significant (see Table 1), but perhaps not practically significant. Both the high performing and the low performing clusters averaged around one inaccurate explanation (*M*=.78 and 1.12, respectively, out of 11 explanations). Rather, the most notable different across the three clusters was engagement in the activity, as was indicated by the number of avoidance explanations. The students in the high performing cluster were the most engaged with the fewest number of avoidance explanations (*M*=0.33 out of 11 explanations avoided); on average, this group engaged in each explanation opportunity. Conversely, the low performing clusters had the highest number of avoidance explanations (*M*=7.27 out of 11 explanations avoided); on average, this group avoided at least half of the explanation opportunities. What appeared to characterize the moderate performing group were paraphrased explanations and inaccurate explanations; moderate performing learners had the highest number of paraphrased explanations (*M*=4.04 out of 11 explanations) and also had the highest number of inaccurate explanations (*M*=2.76 out of 11 explanations).

5. Discussion

Undergraduate students have misconceptions about the biological processes of photosynthesis and respiration that persist through traditional instruction (Anderson et al., 1990; Galvin et al., 2015; Karakaya et al., 2021; Oliver et al., 2018; Södervik et al., 2015). Instructional activities that promote conceptual change are necessary to correct these misconceptions and pave the way for further knowledge building. In this study, we designed an online retrieval practice activity that would activate relevant misconceptions if present and facilitate conceptual change through correct answer feedback and self-explaining. A previous report indicated that self-explaining correct answer feedback is more effective than just receiving it or reading instructional explanations about it (Oliver et al., 2018), and this study explored the types of explanations students produced and which ones were most effective. As such, we asked introductory biology students to complete an online homework activity that prompted them to answer multiple-choice questions about photosynthesis and respiration, and we included common misconceptions in the answer options. After selecting an answer and receiving correct answer feedback, learners were asked to explain why the answer indicated in the feedback was correct. Through a mixed method analysis, we qualitatively analyzed the explanations and developed categories to assign them to. We subsequently coded those explanations and employed quantitative analyses to predict learning outcomes on a test one week later.

Our first research question and qualitative analysis aimed to identify the different types of explanations that students provided about the highly misconceived concepts of photosynthesis and respiration. Using a qualitative-to-quantitative coding process we assessed the explanations learners provided and outlined five categories that explanations fell into: accurate, inaccurate, paraphrase, reflection of knowledge, and avoidance. Accurate explanations occurred when the learners actively engaged in answering the explanation prompt by using their prior knowledge to help explain. Inaccurate explanations occurred when learners actively engaged in answering the prompt and incorporated their prior knowledge into the explanation, but their explanation contained an incorrect statement of facts. These inaccurate explanations were oftentimes the result of incorrect prior knowledge being applied, demonstrating a misconception and the need for conceptual change. Other times, inaccurate explanations resulted from misreading or misunderstanding the question, likely demonstrating inadequate prior knowledge or inattention. Even though students in this study had already learned this content in a previous introductory biology course, inaccurate explanations were not uncommon. In both accurate and inaccurate explanations, the learner added information beyond what was presented in the question or answer.

Paraphrase explanations occurred when students simply restated, either verbatim or paraphrased, parts of the question or answer without adding any additional information from their prior knowledge. These were the most common type of explanation, and they demonstrated a moderate level of engagement with the activity. The learners engaged with the prompt but could not or did not attempt to address "why," which required some amount of elaboration with information from prior knowledge. Avoidance explanations occurred when the learner put something irrelevant in the textbox or otherwise avoided explaining. These explanations served to move the learner through the activity without effort. In some cases, though, these explanations may have indicated that the learner felt incapable of explaining (e.g., "I don't know, I didn't get it right). Avoidance explanations were common in this study, which may not be surprising considering that students were not graded on self-explanation completion or quality.

Reflection of knowledge explanations occurred when learners did not strictly explain the concept but opted to comment on the source of, confidence in, or thoughts about their knowledge. In some cases, these responses demonstrated that the learner was monitoring their prior knowledge and detecting a misconception. In other cases, the learner was simply describing where they learned the information. This category of explanation was an uncommon response type to our self-explanation prompt. The types of self-explanations observed in this study are in line with previous research describing qualities of self-explanations in science. The accurate and reflection of knowledge explanations identified here demonstrate a desirable deep-level of processing, while paraphrased explanations demonstrate more shallow processing (Chinn & Brown, 2000); albeit they still demonstrated more engagement than avoidance. Like other qualitative descriptions of self-explanations, our explanations varied primarily according to engagement and application of prior knowledge (Morrison et al., 2015; Rittle-Johnson et al., 2017; Roy & Chi, 2005). Thus, it appears that the variations in computer-based self-explanations are similar to those observed in other self-explaining formats, but it may be easier for students to avoid engagement with self-explaining on a computer. Our qualitative analysis identified a couple notable findings that deserve further exploration in future work, like the potential interaction between accuracy and engagement.

Our second research question and quantitative analyses predicted test performance based on the types of explanations the student produced. The final multiple regression model weighed the contributions of accurate, inaccurate, and paraphrased explanations, but avoidance explanations and reflection of knowledge explanations were excluded to do multicollinearity and lack of significance, respectively. The model confirmed our initial hypothesis that accurate explanations would have the largest benefit to learning. Indeed, each accurate explanation predicted incremental increases to test performance. the model also confirmed our hypothesis that inaccurate explanations would have no benefits to learning, and they appeared detrimental here. Each inaccurate explanation in our model was associated with a small incremental decrease in test score. Thus, it is important that learners not only explain the correct answer (Rittle-Johnson & Loehr, 2017), but that their explanation of the correct answer is also accurate.

Paraphrased explanations were predictive of learning, albeit their effects on test scores were modest. The distinction between paraphrased explanations and inaccurate explanations here warrants attention. Inaccurate explanations required more engagement from the learner than paraphrased explanations, but that engagement, at least in this online activity covering highly misconceived material, did not result in greater learning. Our results suggest that, if students cannot elaborate on the answer accurately, then it may be better to stick with paraphrasing if additional instructional support is not available.

Reflection of knowledge explanations did not significantly predict learning in our model. This is somewhat surprising, considering that these explanations often included processes key to conceptual change, like the monitoring of prior knowledge accuracy or identifying a conflict between prior and incoming knowledge (Van Den Broek & Kendeou, 2008). It was not particularly common for learners to spontaneously generate this type of explanation in our activity though, and the infrequency of these explanations, relative to the other explanation types, might have contributed to its lack of predictive power in our model. Additionally, conceptual change is not a brief one-and-done process. If these learners were actually engaging in the beginning stages of conceptual change through these explanations, this may not be indicated on the test after a single activity. Some research suggests that meta-cognitive explanations are less effective because they can take attention away from explaining the content itself, but this work was not specific to conceptual change (Bisra et al., 2018). Future work should explore the effects of more deliberate metacognitive self-explanations on conceptual change by directly comparing their effects on conceptual change learning through the experimental manipulation of prompt type. Further, this should be done across multiple instructional sessions to allow sufficient opportunity for the complex process of conceptual change to occur in a measurable way.

Another perspective on the relationship between explanation type and learning was provided by our cluster analysis, which we performed to better understand the role of avoidant explanations. Our two-step cluster analysis categorized learners into three groups. Through these clusters, we were able to see the patterns of explanation types across learners who had high performance, moderate performance, or low performance on the test. Unsurprisingly, high performing students were the most engaged in the activity, had the most prior knowledge, and produced the most accurate explanations. Low performing learners were the least engaged and avoided many of their explanation prompts. They did not tend to produce many inaccurate explanations, but it is unclear what types of explanations they would have produced if engaged.

The most notable of the clusters was the moderately performing group, as they demonstrated an interesting pattern of explanations. This group had both the most paraphrased explanations and the most inaccurate explanations. They had slightly less prior knowledge than the high performing group and generally engaged in the activity. While the mean scores for each group in our cluster analysis are simply descriptive, these trends suggest that the moderately performing group could have benefited from a more open-book format of self-explaining, perhaps that also provides instructional explanations (Hiller et al., 2020). Since the moderately performing group of learners had the highest rate of paraphrased explanations, it is reasonable to assume that they were heavily relying on the information provided in the question and answer to generate an explanation. When they did pull from their own knowledge, they sometimes produced inaccurate explanations. Providing these engaged, yet struggling learners with additional content to aid in the development of their self-explanation likely would have led to more accurate and effective explanations by supplementing inadequate prior knowledge, resolving confusions due to incorrect prior knowledge, and helping alleviate a potentially overburdened working memory load (Leppink et al., 2012).

While it appears that our learners could have benefited from additional instructional support to aid in self-explaining, possible ramifications of doing this should also be considered. Providing unneeded support can hamper learning in high-performing learners (Ayres & Paas, 2012). Additional instructional support can benefit learning in students with low levels of prior knowledge, but sorting through unneeded information can distract students with high-levels of prior knowledge from more productive learning processes; this interaction between knowledge-level and instructional support is known as an expertise reversal effect (Kalyuga et al., 2007; Sweller et al., 2013). The work on expertise reversal effects is not specific to conceptual change processes or instruction, but it does directly address the use of instructional explanations and self-explanations. Future work should investigate interactions between prior knowledge and instructional support more specifically in the context of conceptual change learning, where both the level of prior knowledge and the accuracy of prior knowledge are important considerations.

In the findings presented here, it is worth noting that, while we classified the highest performing students as the high-performing cluster, they still only averaged 71% on the test in session 2. None of the participants demonstrated high levels of prior knowledge in session 1. The overall low levels of performance suggest that learners did not remember much knowledge about these concepts from their previous introductory biology course, and a previous report documenting their performance on the session 1 activity questions indicated that the misconception lures were commonly chosen as answers (Oliver et al., 2018). Thus, at the beginning of their second introductory biology course, these students still had persistent misconceptions about respiration and photosynthesis and had relatively low levels of prior knowledge.

The observed prevalence of avoidance explanations suggests that motivation to fully engage in the activity was low. Students earned credit for sessions 1 and 2 simply by completing them. Both sessions were assigned and described as homework assignments that reviewed content from Introductory Biology I. In an attempt to keep students from looking up the answers online, we made it clear in the instructions that they were not graded on accuracy. Thus, there was no extrinsic motivation for students to perform to the best of their ability. In both practice and research, there is often a trade-off in online asynchronous instruction between disincentivizing cheating or other shortcuts while still motivating high performance. In this study, it is clear that additional extrinsic motivation was needed to incentivize students to engage and perform to their highest ability.

The lack of motivation evidenced by the commonality of avoidance explanations is a limitation of our study. Designing the compensation and framing of these activities to more closely mimic the motivation induced by more formative assessments will be important for future work. Another limitation of our study is the mutually exclusive nature of our categories. With our quantitative analysis in mind, we intentionally designed a single-tiered coding schema during qualitative analysis in which definitions were created so an explanation would only qualify as one category, even if it had components of more than one category. The potential for an explanation to qualify as more than one category only occurred for responses that introduced incorrect prior knowledge (e.g., included knowledge reflection or "I don't know" statements in addition to the introduction of inaccurate prior knowledge). Since inaccurate explanations took precedence over other applicable categories present in the explanation, it could have minimized the frequency of other the categories in doing so (i.e., reflection of knowledge). The use of our single-tiered coding schema may have limited the information we were able to capture from a single explanation, but its purposeful design allowed us to run predictive quantitative models and prioritize the assessment of explanation accuracy—an important focus of our second research question.

6. Conclusions

We draw several conclusions from the results of our qualitative and quantitative analyses of self-explanations content. First, undergraduate students produce a variety of explanations when prompted to self-explain the correct answers to photosynthesis and respiration questions on a computer, and these explanations vary according to engagement, accuracy, and whether they focused on content or reflection. Second, it is ideal for students to use their prior knowledge to elaborate on content in their explanation, but only if their prior knowledge is accurate. Students with misconceptions may apply inaccurate prior knowledge while self-explaining, even if it conflicts with the information they are explaining, and this is detrimental to the learning process. To avoid reinforcing misconceptions with inaccurate self-explanations, students who are unable to produce elaborative and accurate explanations should receive additional instructional support and immediate feedback on the accuracy of their self-explanations. If this is not possible, they would be best advised to focus on accurate paraphrasing. Third, students sometimes opt to spontaneously reflect on their knowledge in self-explanations, but rarely. The types of reflective and meta-cognitive explanations that we observed did not have any effects on learning, perhaps due to low frequency, but their potential utility in conceptual change instruction should be further explored and compared directly with content-based explanations in future work. In conclusion, conceptual change is a complicated process. Without proper feedback and support, instructionally-embedded self-explanation tasks may serve as a double-edged sword in conceptual change instruction, depending on the learners' ability to produce an accurate explanation.

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Appendix 1: 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) CO2 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 C4 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) H2O
C) glucose
D) O2
E) NADPH

7) Which sequence accurately describes the flow of electrons in photosynthesis?

A) Photosystem I → photosystem II → H_2O → NADP
B) Photosystem II → photosystem I → NADP → H_2O
C) H_2O → photosystem II → photosystem I → NADP
D) Photosystem I → photosystem II → NADP → H_2O
E) H_2O → 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_2
E) CO_2

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_2 gas
D) NADPH
E) CO_2 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 NADPþ

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 (NADPþ)
D) reduction of organic carbon, producing inorganic carbon

13) If water labeled with 18O is used in photosynthesis by a green plant, the 18O 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+.
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 2: Revision Activity Questions

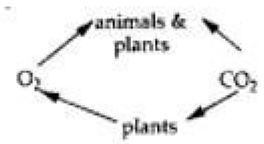
Correct answers are indicated in ***bold***

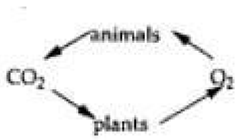
1) Where does the food that a plant needs come from?

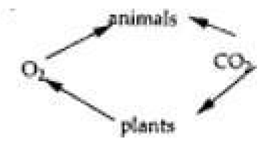
A) The food comes in from the soil through the plant's roots.
B) The food comes in from the air through the plant's leaves.
C) The plant makes its food from carbon dioxide and water.
D) The plant makes its food from minerals and water.

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

A)


B)


C)


D)


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

A) Photosynthesis takes places 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 H20 from the soil into molecules by green leaves
C) Absorption of solar radiation into green leaves
D) Incorporation of CO_2 gas from the atmosphere into molecules by green leaves

8) 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 here for each petri dish.

Results: 1.48g 3.28g 1.17g

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

A) It was converted to CO_2 and H_2O 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?

10) *[Dropped from analysis]* 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 can be broken down during respiration to make ATP.

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

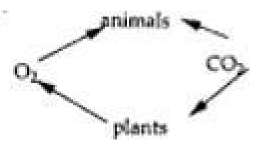
A) It is a chemical process by which plants manufacture food from water and carbon dioxide.
B) It is a chemical process in which energy stored in food is released using oxygen.
C) It is the exchange of carbon dioxide and oxygen gases through plant stomates.
D) It is a process that doesn't take place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

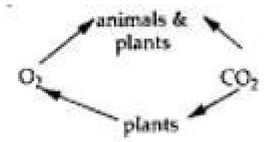
Appendix 3: Test Questions

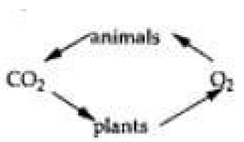
Correct answers are in bold

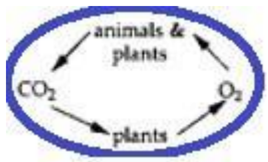
1) Where does the food that a plant needs come from?
   - A) The plant makes its food from minerals and water.
   - B) The food comes in from the soil through the plant's roots.
   - C) The food comes in from the air through the plant's leaves.
   - D) The food comes in both from the soil and the air.
   - **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 places 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 H20 from the soil into molecules by green leaves

Results: 1.48g 3.28g 1.17g

8) 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.

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) *[Previously Activity Item 10 - Dropped from analysis]* 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 care 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. First it was cut at 04:00 am (group A), second 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 o 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?

A) The sugar molecules come from the soil.

B) The sugar molecules are one of many sources of food for plants.

C) The sugar molecules are made from molecules of water and minerals.

D) The sugar molecules are made of carbon atoms linked to other carbon atoms.

18) Which of the following is food for a plant?

A) Sugars that a plant makes
B) Minerals that a plant takes in from the soil
C) Water that a plant takes in through its roots
D) Carbon dioxide that a plant takes in through its leaves

19) The most important benefit to green plants when they photosynthesize is

A) The removal of carbon dioxide from the air through the leaves stomates.
B) The conversion of light energy to chemical energy.
C) The production of energy for plant growth
D) The production of oxygen into the atmosphere

20) Which of the following is true about photosynthesis and respiration in plants?

A) Photosynthesis takes place in the leaves, and those leaf cells respire.
B) Photosynthesis takes place in the green parts of the plant, and the leaf cells respire
C) Photosynthesis takes place in the leaves, and every plant cell respires
D) Photosynthesis takes place in the whole plant, and the leaf cells respire
E) Photosynthesis takes place in the green parts of the plant, and every plant cell respires

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.
A) Photosynthesis occurs only in autotrophs; cellular respiration occurs only in heterotrophs.
B) Photosynthesis uses solar energy to convert inorganics to energy-rich organics; respiration breaks down energy-rich organics to synthesize ATP.
C) Photosynthesis involves the oxidation of glucose; respiration involves the reduction of CO2.
D) 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.
E) 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 ⟶ energy + carbon dioxide + water**.

B. Carbon dioxide + water ⟶ energy + glucose + oxygen.

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

D. Glucose + oxygen ⟶ 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 $\xrightarrow[\textbf{light energy}]{\textbf{chlorophyll}}$ glucose + oxygen

C. Carbon dioxide + water + energy ⟶ 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.

Appendix 4: Codebook Used for Categorizing Explanations

#	Category Name	Description
1	Avoidance	Includes: • Non-answers that were filled in to skip the task. • Shallow responses relating to their method (the answer they selected— "I chose A"; whether they were right or wrong – "I got it right"), • I don't know-type responses • Responses that did not contain a complete thought – "Plants live"
2	Uncodeable	Any explanation that attempted to introduce relevant content but was incoherent and could not be comprehended enough to assign to a category.
3	Paraphrase	Restates or explains without adding new info or referring from prior knowledge. Includes verbatim restatements of parts of the question or answers and paraphrases from the question or answers. These explanations cannot include the introduction of any new information not presented in the question or answers, including the introduction of technical terms not presented.
4	Explains accurately	Explains the correct answer accurately and adds relevant info (terms, concepts, details). The response should be coherent without any inaccuracies.
5	Explains inaccurately	Adds information but contains some level of inaccuracy. Besides introducing incorrect facts/statements, explanations can also be considered inaccurate because they explain the wrong answer as being correct, misunderstood/misread the correct answer/question, or paraphrasing in a way that make it inaccurate. Takes precedent over reflection of knowledge if applicable.
6	Reflection of knowledge	May discuss the source of their prior knowledge or their confidence in their prior knowledge. Prior knowledge could be from a previous question. Knowledge discussed should be accurate. May explains confusion/conflict between their knowledge and the content or point out their own error. Also includes pointing out the misconception without having it (most people think that…).