ENHANCING LEARNING BY TEACHING WITH LEARNER-GENERATED DRAWINGS

by

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Under the Direction of Logan Fiorella

ABSTRACT

This study investigated how learner-generated explanations and drawings foster knowledge building during learning by teaching. College students (n = 120) were randomly assigned to teach a lesson on human respiration by explaining, drawing, or explaining and drawing simultaneously on video. A control group of students did not teach and instead restudied the lesson. All students then completed learning outcome measures one week later. Students who explained and drew simultaneously were expected to produce higher quality explanations (compared to the explain-only group) and perform best on the learning outcome measures. Results indicated all teaching groups outperformed the restudy group and the explain-and-draw group outperformed the explain-only group. As predicted, the explain-and-draw group produced more elaborations in their explanations than the explain-only group, and elaborations partially mediated the relationship between teaching method and learning. These findings suggest that learner-generated drawings can be used to support knowledge building in learning by teaching.

INDEX WORDS: learning by teaching; learner-generated drawing; generative learning strategies; multimedia learning

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CHAPTER 1

INTRODUCTION

There is substantial evidence that teaching others is an effective way to learn (Coleman et al., 1997; Daou, 2015; Fiorella & Mayer, 2013, 2014; Hoogerheide, Loyens, & van Gog, 2014; Hoogerheide et al., 2016; Muis et al., 2015; Nestojko, Bui, & Kornell, 2014; Roscoe, 2014; Roscoe & Chi, 2004, 2007, 2008). Learning by teaching is effective because it is a *generative learning strategy* encouraging students to select the most relevant information from the learning material, organize it into a coherent structure, and integrate it with prior knowledge (Fiorella & Mayer, 2016). Although teaching others generally enhances one's own learning, many students struggle to generate quality explanations during teaching. In their research on peer tutoring, Roscoe and Chi (2007, 2008) found learning by explaining to others only supports deep learning when students generate quality explanations, in which they actively elaborate on the material, monitor their understanding, and incorporate prior knowledge. Roscoe and Chi refer to these active processes as *knowledge building*. Unfortunately, students are more likely to have a bias towards *knowledge telling*, in which students simply restate or summarize the to-be-learned material. For example, when learning about the respiratory system, students may only paraphrase the different parts of the system without actively generating inferences and building a mental model of how the system works. Thus, a major goal of learning by teaching is to identify strategies that encourage students to engage in knowledge building. Previous research has identified some effective supports for fostering knowledge building. For example, providing students with an expectation to teach can enhance motivation and encourage students to think deeply about the material, such as by organizing it in a meaningful way (Fiorella & Mayer, 2013; Fiorella & Mayer, 2014; Muis et. al., 2015; Okita & Schwartz, 2004).

The present study explores whether engaging in other generative strategies while explaining to others can support knowledge building and comprehension during learning by teaching. In particular, learner-generated drawing is an effective generative strategy that is especially effective when learning complex, spatial concepts in science such as the processes in the human respiratory system. One foreseeable benefit of drawing while explaining is that students are able to externalize information onto paper, thereby freeing-up valuable cognitive resources that can then be invested toward generating a better-quality explanation (Sweller, van Merrienboer, & Paas, 1998). Furthermore, research on learning from multimedia suggests students learn better through the integration of text and pictures because it supports inference-making and the construction of a coherent mental model (Mayer, 2014). Research also indicates that learning is more effective when strategies require the integration of multiple representations, such as translating text into a picture or generating an explanation from a provided visual (Cox, 1999; Van Meter & Firetto, 2013; Van Meter & Garner, 2005). Taken together, drawing while explaining may better support knowledge building and comprehension than engaging in either strategy individually. However, to date, research primarily has examined learning by teaching and learning by drawing separately.

Learning by Teaching

Studies on learning by teaching generally suggest generating explanations for someone else enhances one's own learning. For example, in research by Fiorella and Mayer (2013, 2014), college students studied a lesson on the Doppler Effect either with the expectation to teach the material by recording a video lecture to a hypothetical student or with the expectation of taking a test. Of those who expected to teach, some students actually did record a video lecture, whereas others only prepared to teach. Results revealed students who expected to teach and who explained out-loud on video outperformed students who expected to teach but did not explain out-loud on measures of delayed learning. Similar benefits for explaining on video to a hypothetical person have been reported by Hoogerheide and colleagues (2014). Hoogerheide and colleagues (2016) also found students learned better when they generated explanations out-loud to the camera instead of generating explanations on paper.

Although generating explanations to a hypothetical person on video can support learning, many students struggle to generate quality explanations that go beyond the material. In order to strengthen the effectiveness of learner-generated explanations in learning by teaching, Roscoe and Chi (2004) express the importance of fostering knowledge building during student explanations. Knowledge building occurs when students organize relevant information into a coherent structure and incorporate prior-knowledge, to make inferences and elaborate on the learned material. However, research suggests students are more likely to engage in knowledge telling, which involves passively restating the learned material without generating inferences (Roscoe & Chi, 2004, 2007, 2008).

One method for supporting knowledge building in explaining to others is to incorporate questions and feedback from peers. For example, Roscoe and Chi (2004) found tutors are more likely to learn deeply because of questions from the tutee that foster elaborative and monitoring statements during tutor explanations. Furthermore, in his study exploring knowledge building during peer-tutoring, Roscoe (2014) found that the occurrence of knowledge building in explanations significantly predicted comprehension test performance. However, despite the availability of peer feedback, knowledge-building occurred during only 6% of all explanations.

Thus, there is a need for additional methods for fostering knowledge building during explaining and helping students overcome their bias to engage in knowledge telling. One limitation of the current research on learning by teaching is that it has focused on learner-generated explanations as an independent strategy. Using learning by teaching in combination with other types of strategies, such as learning by drawing, may help to better support the construction of quality explanations.

Learning by Drawing

Learning by drawing involves generating a representative illustration that depicts the appearance of a physical system, such as the structure of a neuron or the structure of a bird's wings (Van Meter, 2001). Research suggests drawing is generally an effective strategy for learning from text, particularly in science texts that describe complex spatial relationships (Gobert & Clement, 1999; Hegarty, Carpenter & Just, 1991; Scheiter, Schleinschok, & Ainsworth, 2017). For example, Gobert and Clement (1999) found students who drew while reading about plate tectonics performed better on a post-test assessing the spatial and causal information from the text than students who generated summaries or only read the text.

Similar to learning by explaining, the effectiveness of learning by drawing depends on the quality of the drawings students generate (Schwamborn et. al., 2010). For example, in a study by Scheiter, Schleinschok, and Ainsworth (2017), students either self-explained or drew as they read a scientific text about greenhouse gases. Results indicated that there were no overall learning differences between the groups; however, when the quality at which students drew or explained was taken into account, generating quality drawings was a better predictor of performance than generating quality explanations.

Other research suggests that drawing quality can be enhanced by providing instructional support. For example, in a study by Van Meter and colleagues (2006), students either drew with support from provided illustrations or prompting questions or drew without support. Students who drew with some support had higher quality problem solutions than students who drew without support or did not draw at all. Furthermore, Schmeck and colleagues (2014) found drawing-accuracy scores significantly predicted students' performance on a subsequent comprehension test. Overall, research on learning by drawing suggests that generating drawings can enhance learning, and that drawing quality predicts learning (Schwamborn, Mayer, Thillmann, Leopold, & Leutner, 2010).

According to Van Meter and Firetto (2013), generating drawings provides unique cognitive and metacognitive benefits. In their Cognitive Model of Drawing Construction, Van Meter and Firetto posit that drawing is beneficial for learning because it facilitates the externalization of the structural representations present in a mental model. Furthermore, when students are given the opportunity to generate and externalize important information, they are better able to refer back to and update the information in their mental model. Thus, the unique benefits of generating drawings might help support knowledge building while generating an explanation because students are better able to externalize some information in a salient way that explanations cannot (i.e., physical drawing vs. verbal explanation). Previous research has primarily examined these strategies independently; the purpose of the present study is to test whether drawing supports the construction of quality explanations during learning by teaching.

Integrating Explaining and Drawing

The previous sections have outlined how learning by explaining to others and learning by drawing are effective strategies when used independently. Research on learning from *provided* *representations,* which are text or pictorial information that foster the construction of a mental model, suggests using both strategies simultaneously might better support meaningful learning. For example, research on multimedia learning suggests integrating multiple types of provided representations (e.g., verbal and nonverbal) better supports meaningful learning. According to the Cognitive Theory of Multimedia Learning (Mayer, 2009), students learn better when studying provided text and visuals rather than text alone because integrating verbal and nonverbal representations supports the construction of an accurate mental model. Similarly, according to the Cognitive Model of Drawing Construction (Van Meter & Firetto, 2013), creating drawings involves the forced integration of verbal and non-verbal representations, such that students convert the provided text into an illustration. In short, both models emphasize the importance of integrating text and pictures by selecting the most relevant information, organizing it into a coherent mental representation, and integrating it with existing knowledge.

Research on studying visuals also suggests engaging in strategies that foster the integration of multiple representations is beneficial for learning. For example, in a study by Ainsworth and Loizou (2003), students reviewed a lesson on the circulatory system that included provided text or provided text and visuals and later self-explained what they studied. Students who generated explanations of texts and visuals had higher quality explanations than students who generated explanations of only text. This research suggests self-explanation can help foster the integration of multiple representations when studying provided visuals. An open question is whether learner-generated drawings can support the construction of learner-generated explanations.

One potential benefit of drawing while explaining is that such as strategy makes more efficient use of students' limited working memory resources. Cognitive load theory (Sweller,

2011) posits that instruction should seek to diminish extraneous (i.e., not beneficial for learning) processing and foster germane (i.e., beneficial or generative) processing. While generating an explanation out-loud, students may engage in extraneous processing because they must hold pertinent information in working memory, while simultaneously constructing or updating their mental model. Generating drawings while explaining may help to limit extraneous processing because drawings fosters *computational offloading*, in which external representations are used to reduce the amount of cognitive effort required to complete a task (Ainsworth, 2006). In the case of drawing and explaining, drawing offloads information onto paper in a way that frees-up enough cognitive capacity so that students are not required to continually hold important information in working memory while also generating an explanation. This further allows students to devote more working memory resources towards making inferences, generating elaborations, and incorporating prior knowledge into their explanations.

Drawing, while explaining, should help students to better regulate their learning. Van Meter and Firetto (2013) suggest when students draw, they set standards for one's performance, apply operations, and monitor their progress. For example, in a study by Schleinschok, Eitel, and Scheiter (2017), students were asked to draw as they read an expository text or only read the text. Students who drew while they read reported more accurate judgements of learning over students who did not draw, which was predictive of their posttest performance. Similarly, in their work on peer tutoring, Roscoe and Chi (2004, 2007) report the importance of self-monitoring while students generate explanations. Taken together, explaining and drawing may work together to foster self-monitoring during learning by teaching. Specifically, students can use their constructed spatial representation (drawing) to support their constructed verbal representation (explanation) and continually use both representations to iteratively update and repair their mental model.

The Present Study

The present study tested whether generating drawings during learning by teaching better fosters knowledge building and long-term learning outcomes. In the study, college students were asked to study a text lesson on the human respiratory system and then teach the material to a hypothetical person by explaining, drawing, or explaining and drawing simultaneously on video. A control group of students did not teach the material, but instead spent the same amount of time restudying the lesson. Learning outcomes were measured one week after the intervention. Overall, this study investigated how learner-generated drawings can support the quality of learner-generated explanations during learning by teaching.

Taken together, learner generated explanations and learner generated drawings are effective for learning from scientific texts. However, the current research on learning by teaching and learning by drawing has yet to look at the relationship between these two strategies when paired together. As such, the purpose of the present study was to explore whether students' knowledge of the human respiratory system improved after explaining, drawing, or engaging in both teaching strategies simultaneously. Moreover, to our knowledge, no study has looked at how explanation and drawing quality interact to support learning by teaching. Therefore, this study investigated what the role of explanation and drawing quality is when learning from learner-generated explanations and/or drawings. Thus, our hypotheses relate to differences between the groups on overall learning outcomes and explanation or drawing quality.

Considering the findings from Ainsworth and Loizou (2003), we predict that students who explain and draw will show superior long-term learning outcomes compared to students who only explain, only draw, or restudy (H1a). Because our primary goal is to test whether drawing supports learning by explaining, this study is particularly interested in the comparison between the explain-and-draw group and the explain-only group. Next, we predicted that engaging in a teaching strategy (explain-only, draw-only, or explain-and-draw) will result in better learning outcomes than restudying without teaching (H1b). Finally, given that drawing has been shown to better support learning outcomes in science than verbal strategies, such as summarizing or written explanations (Gobert, & Clement, 1999; Leopold & Leutner, 2012; Scheiter, Schleinschok, & Ainsworth, 2017), we predicted that the draw-only group would outperform the explain-only group on learning outcome measures (H1c).

An additional consideration is the role of explanation and drawing quality in fostering learning. First, we predicted that students who explain and draw simultaneously will generate higher quality explanations (i.e., more elaborations) than students who only explain (H2a). Furthermore, we predicted explanation quality will be significantly correlated with learning outcomes for the two groups who explained (H2b). Given the lack of relevant past research, we did not have strong a priori predictions regarding the differences between the explain-and-draw group and the draw-only group on drawing quality (H2c). We also predicted that drawing quality, like explanation quality, will be significantly correlated with learning outcomes for the groups who drew (H2d). Lastly, we predicted that the relationship between teaching method (i.e., explain-only or explain-and-draw) and learning outcomes will be mediated by explanation quality (i.e., occurrence of elaborations) (H3).

CHAPTER 2

METHOD

Participants and design

The participants were 120 undergraduate students from the University of Georgia. Participants were recruited both from the Educational Psychology participant pool and undergraduate courses. Students received compensation for their participation either through course credit or a $20 gift card. Participants were randomly assigned to one of the four conditions. There were 30 students in the restudy group, 30 students in the explain-only group, 30 students in the draw-only group, and 30 students in the explain-and-draw group. The mean age of participants was 19.82 years (*SD* = 1.68), and there were 25 men and 95 women. The groups did not significantly differ on mean age, $F(3, 119)=1.369$, $p > .05$.

Materials

The materials consisted of a consent form, a demographics questionnaire, a pre-test, a lesson on the human respiratory system, and learning outcome measures. Most of the materials were presented to students on the computer using MediaLab software. The consent form and post-test were provided on paper. The consent form described the details of the study and informed participants they may be videotaped and recorded during the experiment.

The demographics questionnaire asked participants to provide their age, gender, and to self-report their interest in learning about biology on a five-point scale ranging from 1 (strongly disagree) to 5 (strongly agree). Students were also asked to self-report prior experience with learning in biology by placing a check mark next to each of the following items that applied to them: “I have participated in science programs or fairs,” “Biology was my favorite subject in high school,” “I sometimes watch science documentaries about anatomy in my free time,” “I can name most of the components of the human heart from memory,” and “I have taken a course in human anatomy or physiology.”

The pre-test consisted of one free-response question asking students to write down everything they know about the human respiratory system. The learning outcome measures consisted of a retention test, a drawing test, and a transfer test. The retention test consisted of one free-response item asking students to recall as much as they can about the process of respiration. The drawing test consisted of two items asking students to draw and label the parts of human respiratory system and the parts and processes involved in exchange. The transfer test consisted of five free-response items requiring students to apply what they learned about the respiratory system to new situations, for example: “Suppose there is oxygen in the lungs, but the cells in the body do not get enough oxygen to make energy. What could have caused this problem?”, “How could you redesign the human respiratory system to make it more effective in climates where less oxygen is in the air (such as at the top of tall mountains)?”, “How does a person’s lung size affect their respiration?”, “What would happen if a person’s diaphragm does not move during inhaling?”, and “The blood moving from the cells of the body into the heart to be transported into the capillaries is red instead of blue. What is wrong with the exchange system?”

Each of the three learning outcome measures was highly correlated with each other (r’s > .50, ps < .05). Furthermore, reliability analyses indicated the assessment is more reliable when each of the three measures are combined ($\alpha = .75$) rather than separate (drawing test: $\alpha = .58$; transfer test: $\alpha = .66$). Therefore, we created a composite learning outcome score by averaging the z scores across the three different tests.

Learning Material

The learning material consisted of a ten-paragraph lesson on the human respiratory system. The lesson explained the structures and processes involved in the nervous system, thoracic cavity, airway system, exchange system, and circulatory system. Each paragraph was presented on an individual PowerPoint slide on the computer (see Appendix A).

Coding and Scoring

Coding Explanations (Explain-Only and Explain-and-Draw Groups)

Each explanation was transcribed verbatim by a researcher. Any ambiguities in the audio were flagged for another researcher to listen to and check for accuracy.

The full transcripts were then broken down into individual episodes. An episode would begin and end based on its adherence to an idea unit presented in the lesson. An episode begins when a participant transitions to a new idea unit in the lesson, for example, "*And then in the lungs is where the gas exchange happens. The gas exchange is between carrying oxygen or oxygen and carbon dioxide through the body. Oxygen is what your cells need to function. CO2 is the waste caused by it"* and "*around the bronchial tubes there are air sacs called alveoli. And that is where oxygen and CO2 is temporarily held."*

Scoring Episodes

The explanation coding system was adapted from Roscoe and Chi (2004; 2008), who distinguished between knowledge building and knowledge telling. The scoring protocols developed by Roscoe and Chi provided a general framework for coding students' explanations, in which knowledge building and telling were two primary categories where students received points. Knowledge telling consisted of idea units explicitly stated from the lesson, whereas knowledge building consisted of elaborations and monitoring statements.

Knowledge Telling: Knowledge telling is paraphrasing idea units from the lesson with no elaboration. Common examples of knowledge-telling are summary statements (Roscoe, 2014). There are a total of 96 possible knowledge telling idea units in the respiratory system lesson. Participants received one point for each telling unit included in their explanation. For example, knowledge telling statements include: *"[A]nd then in the lungs is where the gas exchange happens."* and *"[A]round the bronchial tubes there are air sacs called alveoli."*

Elaboration Statements: Elaboration is a component of knowledge building because it involves going beyond what is stated in the lesson by incorporating one's existing knowledge. Participants received one point for each attempt to explain the material beyond what is provided in the text. Types of common elaborative statements include analogies, examples, and comparisons. For example, elaborative statements include, *"…little air sacs called alveoli's, which basically are like little bubbles"* and *"[S]urrounding the alveoli is these little nets, called capillaries."* Elaborations also consist of statements that incorporate students' existing knowledge, such as a student referring to "hemoglobin," which was not explicitly mentioned in the lesson.

Monitoring Statements: Knowledge building also consists of monitoring statements, which involve reflection on one's understanding of the material. A monitoring statement might express confusion, a misconception, or it might seek to repair a previous statement that was inaccurate. Participants received one point for each monitoring statement made during an episode. For example, monitoring statements include, *"where is the command center of your brain? OH! I just said it…"* and *"…muscles surrounding it. Yeah, that was really out of order."*

Two researchers coded a sample of eight participants' explanations to determine interrater reliability. Interrater reliability was high at $r = .991$ ($p < .01$). One rater scored the remaining explanations.

Scoring Drawings (Draw-Only and Explain-and-Draw Groups)

Components: Drawings were scored for accuracy using the same content used to score knowledge telling statements in students' explanations. Participants received one point for each accurate component (item) included in their drawing.

Relationships: Drawings were also scored for accurate relationships. Participants received one point for each accurate relationship when they correctly expressed through pictures or words how the components in the respiratory system work together to function. Participants had to clearly express the relationship between components in the system through words or images that included arrows or other symbols that clearly signal a process.

Procedure

The study consisted of two parts that occurred over two weeks. The first part of the study took approximately forty-five minutes and the second part took thirty minutes to complete. The participants were randomly assigned to one of the four groups: explain-only, draw-only, explain-and-draw, or restudy.

First, participants read and signed an IRB approved consent form and then completed the demographic questionnaire and pretest. Then they were given provided instructions for completing the learning phase. During the learning phase, participants were given twenty minutes to study the PowerPoint presentation on the human respiratory system and take notes; however, they were instructed that they would not be able to view their notes during a test or while they teach. Participants in the teaching conditions were given instructions to study the lesson in a way that would help them to explain, draw, or explain and draw the material on video to a hypothetical student who was not familiar with the material. The restudy group was asked to study the lesson in a way that would help them perform well on a test. After the instructions, the researcher asked participants if they had any questions and confirmed that the participants had a clear understanding of how they should be studying during the learning phase.

After completing the learning phase, students in the teaching conditions taught the material on video by either explaining out-loud, drawing on paper, or explaining out-loud and drawing on paper simultaneously. Participants who taught were given up to eight minutes to record their video lesson; participants in the restudy condition were given eight minutes to restudy the lesson. After teaching or restudying, participants were thanked for completing Part 1 of the study and reminded to return one week later to complete Part 2.

Participants then returned one week later to complete the learning outcome measures. During this phase, participants were given the posttest that consisted of eight free-response questions. The participants had four minutes each to complete the first three questions (retention and drawing questions) and three minutes each to complete the remaining questions (transfer questions). The participants were asked to use all of the time provided to answer the questions and not move forward until the time for each question was over. After completing the post-test, participants were thanked and compensated with either course credit or a $20 gift card.

CHAPTER 3

RESULTS

Preliminary Analyses

An analysis of variance was conducted to test whether the four groups significantly differed on prior knowledge and topic familiarity. There were no significant differences between the groups on topic familiarity, $F(3, 119) = .29$, $p > .05$. However, there was a significant difference between the groups on prior knowledge, $F(3, 119) = 3.34$, $p < .05$. A Tukey post hoc analysis indicated the restudy group performed significantly better on the prior knowledge test than the draw-only group ($p = .026$). Post hoc results also indicated the restudy group was close to performing significantly better on the prior knowledge test than the explain-and-draw group ($p = .05$). Therefore, prior knowledge was used as a covariate on all subsequent analyses relating to learning outcomes.

Did the groups differ on learning outcomes?

Table 1 presents the means and standard deviations for learning outcomes across the four groups. Hypothesis 1a predicted students in the explain-and-draw group would outperform students in the other three groups on learning outcome scores. An analysis of covariance between the groups with prior knowledge revealed there was a significant difference between the groups on learning outcomes, $F(3, 115) = 16.271$, $p < .001$. Bonferroni pairwise comparisons revealed the explain-and-draw group significantly outperformed the explain-only ($p = .001$) and restudy groups ($p = .000$) on learning outcome measures; the difference between the explain-and-draw and draw-only group did not reach statistical significance (p = .067). Overall, these results mostly support hypothesis 1a.

Hypothesis 1b predicted all teaching groups would outperform students who restudied. Consistent with this prediction, Bonferroni pairwise comparisons indicated that each of the teaching groups significantly outperformed students in the restudy group (p's $\leq$ .01). Finally, the draw-only group did not significantly outperform the explain-only group (p = .56), indicating that Hypothesis 1c was not supported.

Did the groups differ in explanation and/or drawing quality?

Table 1 also reports the means and standard deviations of explanation and drawing quality for each of the teaching groups. Hypothesis 2a predicted students who generated explanations and drawings would have higher quality explanations (i.e., more elaborations) than students who only generated explanations. Consistent with this prediction, the explain-and-draw group generated significantly more elaborations in their explanation than those in the explain-only group, $t(55) = -2.759$, $p < .05$. A t-test between the explain-only and explain-and-draw group indicated that the groups did not significantly differ on the occurrence of knowledge telling, $t(55) = .008$, $p = .994$, or monitoring statements, $t(55) = .170$, $p = .866$, included in their explanations. Hypothesis 2b predicted that explanation quality would be significantly positively correlated with learning outcomes. Consistent with this prediction, results indicated that there was a significant positive correlation between explanation quality (i.e., elaborations) and learning outcomes, $r = .40$, $p < .01$.

Figure 1 shows student-generated drawings that represent a low-quality and high-quality drawing. Hypothesis 2c explored possible differences in drawing quality between the draw-only and explain-and-draw groups. Results indicate that the draw-only group had significantly more components and relationships (i.e., drawing quality) in their drawings than those in the explain-and-draw group, $t(58) = 2.54$, $p < .05$. However, there was not a significant correlation between drawing quality and learning outcomes, $r = .132$, $p > .05$, thus not providing support for hypothesis 2d. Overall, these results suggest that the explain-and-draw group outperformed the other groups on learning outcome measures, which may be at least in part due to generating better quality explanations during teaching.

Table 1

Learning outcomes (z-scores) for the four groups and explanation and drawing quality for the three teaching groups.

Strategy	Explain-only		Draw-only		Explain-and-Draw		Restudy	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Learning Outcomes	-0.3	1.5	0.4	1.8	1.8	2.6	-1.9	2.6
Explanation Quality (elaborations)	2.9	3.5	-	-	6.2	5.1	-	-
Drawing Quality (components & relationships)	-	-	31.3	11.1	23.1	13.9	-	-

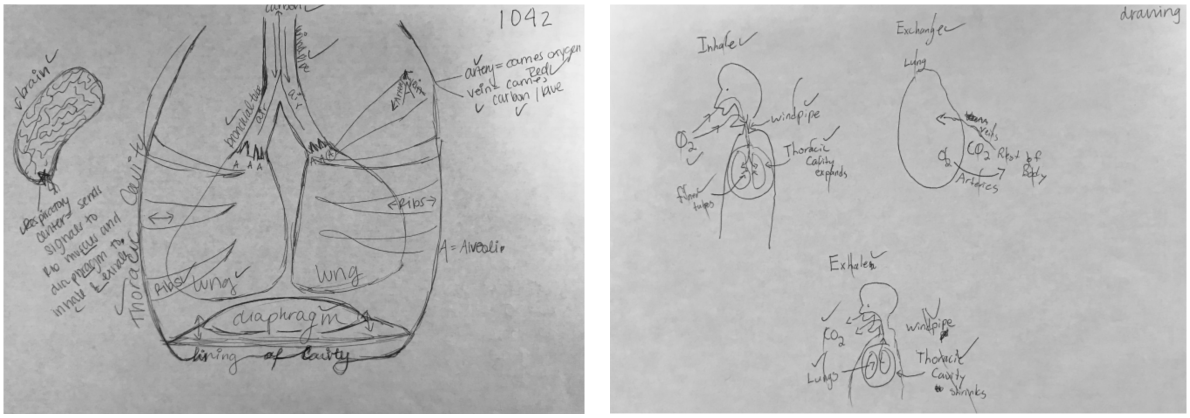

Figure 1. Student drawings comparing a high quality (left) and low quality (right) drawing

Does teaching quality mediate the relationship between teaching method and learning outcomes?

Hypothesis 3a predicted differences in learning outcomes between the explain-only and explain-and-draw groups would at least in part be explained by the explain-and-draw group generating better quality explanations (i.e., more elaborations) during teaching. Thus, a mediated regression analysis was conducted based on guidelines from Barron and Kenny (1986) to test whether explanation quality mediates the relationship between teaching method (explain-only or explain-and-draw) and learning outcomes. First, the direct effect of teaching method on learning outcomes was statistically significant ($\beta = .451$; $SE = .275$), $t(55) = 3.851$, $p < .001$, such that the explain-and-draw group outperformed the explain-only group. Second, the path from teaching method to elaborations was statistically significant ($\beta = .349$; $SE = .581$), $t(55) = 2.759$, $p = .008$, indicating that the explain-and-draw group generated more elaborations than the explain-only group. Finally, when teaching method and elaborations were regressed on learning outcomes simultaneously, the path from elaborations to learning outcomes was statistically significant (β =

.290; *SE* = .064), *t*(55) = 2.312, *p* = .025, and the path from teaching method to learning outcomes remained statistically significant (β = .325; *SE* = .293), *t*(55) = 2.59, *p* = .012. In addition, this reduction was statistically significant (z = 1.86, *p* = .03). Thus, consistent with Hypothesis 3a, the relationship between teaching method and learning outcomes was partially mediated by explanation quality. Figure 2 depicts the results of the mediation analysis.

Last, because we did not find support for a significant relationship between drawing quality and learning outcomes, we could not analyze drawing quality as a possible mediator in the relationship between teaching method (draw-only or explain-and-draw) and learning outcomes (hypothesis 3b).

Mediation Analysis of Teaching Group, Elaborations, and Learning Outcomes

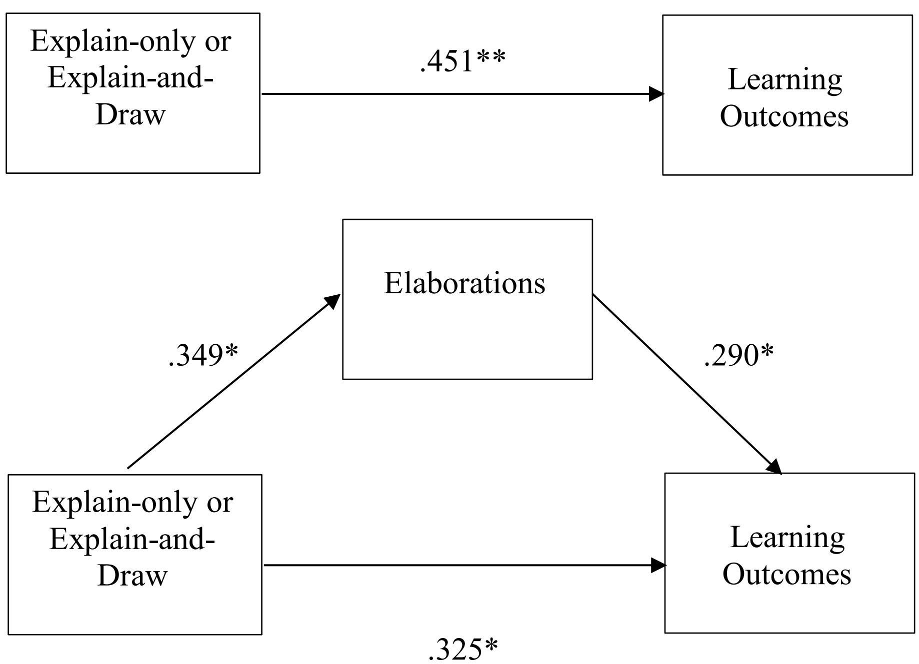

Figure 2. Mediation analysis of teaching group, elaborations, and learning outcomes.

*p < 0.05, **p < 0.001.

CHAPTER 4

DISCUSSION

Prior research suggests learner-generated drawings and explanations can help foster generative processing and meaningful learning from scientific text. The present research sought to explore the potential complementary role of drawing and explaining simultaneously within the context of a learning by teaching activity. Specifically, the primary goal of the present study was to test whether the act of generating drawings supports better quality explanations and results in better learning outcomes than only explaining. To test this hypothesis, students taught the contents of a lesson on the human respiratory system by explaining, drawing, or explaining and drawing on video to hypothetical students. The following sections discuss the study's major findings and its theoretical and practical implications.

Empirical Contributions

Results from the present study generally supported our primary hypotheses regarding learning outcomes and explanation quality. First, the explain-and-draw group generally outperformed the other groups on delayed learning outcomes. This finding is consistent with our prediction that explaining and drawing can serve as mutually supportive strategies. In particular, the findings supported our primary prediction that the explain-and-draw group would outperform the explain-only group. This finding suggests drawing can be used to foster long-term learning in learning by teaching. Furthermore, students who taught on video – either by explaining, drawing, or both – outperformed the restudy group on learning outcomes. This finding is consistent with prior research on learning by teaching and generative learning strategies (Fiorella & Mayer, 2016). Last, results indicated there was no significant difference in performance between the draw-only and explain-only groups. This finding is inconsistent with our prediction and suggests that explaining and drawing are potentially comparable generative strategies for fostering learning, when used independently.

Next, this study found drawing while explaining influenced the quality of students' explanations. Specifically, students in the explain-and-draw group generated more elaborations while explaining than the explain-only group. This outcome suggests learner-generated drawings foster knowledge building during learner-generated explanations. Subsequently, results indicated the draw-only group generated higher quality drawings than the explain-and-draw group. This finding is not surprising considering that students who drew-only provided more information in their drawings than students who explained and drew. Importantly, results indicated that explanation quality (i.e., elaborations) had a significant positive relationship with learning outcomes, while drawing quality did not have a significant relationship with learning outcomes. This finding supports that explanation quality is a necessary process for superior performance on the learning outcome measures. Furthermore, learner-generated drawings and explanations foster knowledge building during learning by teaching, which then leads to deeper and long-term learning.

Finally, analyses revealed explanation quality partially mediated the relationship between teaching group for the explain-only and explain-and-draw groups and learning outcomes. This finding is consistent with our prediction that explanation quality would be a necessary process for the relationship between teaching group and learning outcomes. This evidence suggests that drawings worked as a mechanism for supporting knowledge building during learning by teaching.

Theoretical Contributions

These findings suggest generating an explanation and drawing simultaneously foster generative processing necessary for long-term learning. This is generally consistent with *generative learning theory* and learning from multimedia. Superior performance on learning outcome measures by the explain-and-draw group support that students were able to select the most relevant information from the lesson, organize it into a coherent representation, and integrate it with prior knowledge (Select-Organize-Integrate Model; Mayer, 2009). Additionally, this finding aligns with the Cognitive Theory of Multimedia Learning (Mayer, 2005) and the Cognitive Model of Drawing Construction (Van Meter & Firetto, 2013), which suggest that information processed in both the pictorial and verbal channel of working memory is more likely to foster an organized mental model.

Although the current study does not provide direct measures of the processes fostering explanation quality, results suggest processing was likely due to benefits to working memory. Importantly, it was unclear whether explaining and drawing simultaneously would help or hinder learning because engaging in two strategies together could be generative by fostering deep thinking or extraneous on the demands of working memory. If engaging in the two strategies simultaneously was extraneous for cognitive processing, explaining and drawing together would not have been beneficial for learning; however, our findings supported the opposite. Thus, our results have important implications for Cognitive Load Theory (Sweller, 2011) and indicate that simultaneous learner-generated drawings and explanations foster generative cognitive processing that is beneficial for long-term learning.

Additionally, this study provides implications for self-regulatory learning while generating explanations and drawings. Previous research has supported learner-generated drawings and explanations as strategies for fostering self-regulatory learning (Kostons & Koning, 2017; Muis et. al., 2016; Schleinschok, Eitel, & Scheiter, 2017; Van Meter & Frietto, 2013). Although this study did not find a significant difference in monitoring statements between the explain-only and explain-and-draw groups, it is still possible that students were monitoring their learning in a way that was not best captured by our measures.

Last, results indicated that explanation quality significantly contributed to better learning outcomes for the explain-only and explain-and-draw group. Thus, this evidence supports previous research that has established the importance of strategy quality when generating explanations and drawings. Roscoe and Chi (2007) suggest learners must engage in knowledge building while explaining and Schwamborn and colleagues (2010) suggest that the quality of learner-generated drawings must be reflective of the generative processing occurring during drawing. Findings from this study support and expand on this rationale by finding that knowledge building is better supported by generating drawings and explanations simultaneously during learning by teaching. Thus, learning from explaining and drawing simultaneously requires learners to engage in generative processing that connects verbal and pictorial information together and with relevant prior knowledge, which fosters elaborative statements and inference-making (Mayer, 2005).

Overall, this study provides interesting implications for research on generative strategies that foster learning, particularly learner-generated explanations and drawings. Previous research on generative strategies has explored explaining and drawing separately. This study begins to explore how learning can be more meaningful when explaining and drawing are used simultaneously.

Practical Contributions

This study provides important practical implications for the use of generative learning strategies. Considering this study's novel approach to explore explaining and drawing together, it provides insight into how integrating multiple learner-constructed representations can support learning. Previous research on multiple representations has mostly examined how provided verbal and pictorial representations are presented together or how a verbal strategy can support learning from a pictorial representation. The findings from this study suggest strategies for learning from text are more effective when they incorporate multiple modalities.

Specifically, this study indicates that learner-generated drawings can be used to support better quality explanations. Research on learning by teaching emphasizes the importance of knowledge building when students are generating explanations; however, students have a strong bias towards knowledge telling. This study provides an effective way for fostering knowledge building during learning by teaching. Drawing while explaining may be a useful technique for enhancing one's individual studying, as well as common classroom practices, such as peer-tutoring. This strategy is particularly useful for learning in science, which requires students to mentally maintain and integrate complex verbal and spatial information. Overall, the use of learner-generated drawings as a support for learner-generated explanations can better support long-term learning than using either strategy separately.

Limitations and Future Directions

One limitation of this study is that the learning outcome measures had low reliability when they were used in isolation. Prior research suggests generative strategies such as drawing and explaining are more likely to have a greater effect on transfer test performance (Leopold & Leutner, 2012; Schmidgall, Eitel, & Scheiter, 2018), though we were unable to focus specifically on transfer test performance in the present study. The evidence for learning outcomes may have been more pronounced between the explain-and-draw and draw-only groups if a reliable transfer test were used as the primary learning outcomes measure.

Another limitation of this study is that it did not directly assess the role of cognitive load and self-regulatory processing. Cognitive load and self-regulated learning are important processes for understanding how explaining and drawing benefit learning. Future research should seek to better explore these mechanisms by incorporating more direct process measures, such as student's cognitive load ratings or judgements of learning. Furthermore, future research should explore other mechanisms – in addition to elaborations – that contribute to the benefits of drawing while explaining.

Future work should also seek to explore the role of motivation in learning from generating explanations and drawings. Evidence from peer-tutoring and learning by teaching research suggests that motivation plays an important role in learning outcomes (Coleman, 1997; Fuchs et al., 1997; Hoogerheide, Loyens, & van Gog, 2014; King et al., 1998). For example, Okita and Schwartz (2004) found that students were more motivated to think deeply about the learning material when they knew they would be expected to later teach the material to another student. Future research should explore whether explaining and drawing during learning by teaching have unique effects on student motivation.

Finally, future work should consider how the effects from this study can be applied to the classroom. Learning by explaining has been incorporated in the classroom through peer-tutoring programs (Roscoe & Chi, 2007; Roscoe, 2014) and learning by drawing is a common strategy for learning in science (Scheiter, Schleinschok, & Ainsworth, 2017; Gobert & Clement, 1999; Hegarty, Carpenter & Just, 1991); however, research has not yet examined how these strategies can be simultaneously integrated within classroom practices. Overall, the present study provides an important first step for understanding the complementary roles of explaining and drawing. Further research is needed to better understand the precise cognitive, metacognitive, and motivational processes underlying learning by explaining and drawing.

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APPENDICES

Appendix A

Lesson on the Human Respiratory System

1. Introduction

Respiration is the process that moves air in and out of the lungs. Through respiration, oxygen is delivered to where it is needed in the body and carbon dioxide is removed from the body. Respiration involves three phases: Inhaling, exchanging, and exhaling. The respiratory process is controlled by the nervous system.

2. Structure of the Nervous System

The respiratory center is located in the rear, bottom part of the brain, near the back of the neck. The respiratory center of the brain is connected to a pathway of nerves that leads down from the spinal cord to connect with muscles controlling the diaphragm and rib cage.

3. Steps in the Nervous System to Control Breathing

When the brain detects the need for more oxygen in the bloodstream, the respiratory center in the brain sends out a signal to inhale. The signal moves along the pathway of nerves to muscles controlling the diaphragm and rib cage. When the brain detects the need for less carbon dioxide in the bloodstream, the respiratory center in the brain terminates the signal to inhale and initiates the signal to exhale. The signal to exhale then moves along the pathway of nerves to the muscles controlling the diaphragm and rib cage.

4. Structure of the Thoracic Cavity

The thoracic cavity is the space in the chest that contains the lungs. It is surrounded by the rib cage, which can move slightly inward or outward, and the diaphragm on the bottom, which has a dome that can move downward. The main muscles involved in respiration are the diaphragm and the rib muscles. The diaphragm is located underneath the lungs. It lines the lower part of the thoracic cavity, sealing it off from the rest of the body. The rib muscles are attached to the ribs, which encircle the lungs. When in the relaxed position, the ribs are slightly inward and the diaphragm dome curves upward.

5. Structure of the Airway System

Air comes through either the nose or mouth and is led down the windpipe. From the windpipe, air travels to the bronchial tubes which branch off into the right and the left lung. There they branch off into finer tubes.

6. Process of Inhaling

During inhaling, a signal from the brain to inhale causes the dome of the diaphragm to contract downward and the rib cage to move slightly outward creating more space in the thoracic cavity so that the lungs can expand. Air is drawn in through the nose or mouth, moves down through the windpipe and bronchial tubes to tiny air sacs in the lungs.

7. Structure of the Exchange System

Tiny air sacs, called alveoli, are grouped together in the lungs at the bronchial tubes. Each alveoli is surrounded by tiny blood vessels called capillaries. On one side of the alveoli the surrounding capillaries carry oxygen; on the other side, they carry carbon dioxide. Oxygen-carrying capillaries connect alveoli to larger blood vessels called arteries, which are represented as red because they contain an abundance of oxygen. Carbon-dioxide-carrying capillaries connect alveoli to larger blood vessels called veins, which are represented as blue because they contain an abundance of carbon dioxide.

8. Structure of the Circulatory System

Arteries run from the lungs, through the heart, to the cells of the body. Arteries transport oxygen, which is used by the cells of the body to make energy. Veins run in the opposite direction from the cells of the body, through the heart, to the lungs. Veins transport carbon dioxide, which is a waste gas produced in the cells of the body. The heart is a pump that keeps the blood flowing in the veins and arteries.

9. Process of Exchanging

The exchange of oxygen and carbon dioxide takes place in the connection between the alveoli and capillaries in the lungs. Oxygen molecules that are contained in the inhaled air move to the capillaries, while carbon dioxide molecules that are contained in the inhaled air move from the capillaries into the alveoli. The capillaries then carry the oxygen to arteries, which then transport it through the heart and into the cells of the body. At the same time, carbon dioxide is removed from the cells of the body and moved to the heart through veins. From the heart, it is sent to the capillaries and into the alveoli, where carbon dioxide from the air is already being stored.

10. Process of Exhaling

The carbon-dioxide-rich air in the alveoli is drawn out of the lungs by exhaling. When the brain turns off the signal to inhale, the diaphragm and the rib muscles relax. The dome of the diaphragm moves upward again and the ribs move slightly inward. As a result, the thoracic cavity becomes smaller creating less room for the lungs. Air containing carbon dioxide is forced out of the lungs through the bronchial tubes and windpipe to the nose and mouth, where it leaves the body.