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Using Worked-Out Examples of Written Explanation for Writing-to-Learn in Evolutionary Biology

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A thesis submitted in partial fulfillment of the requirements for the degree in Master of Arts

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by

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Abstract

Content learning can be enhanced through writing-to-learn. Research into cognitive load theory suggests that the use of backwards faded, worked-out examples increases schema acquisition and concept transfer. However, these effects have not yet been demonstrated for writing-to-learn, particularly for the conceptual understanding of evolution. The effects of two writing conditions were investigated in a pre-test post-test quasi-experimental design. Groups in two conditions wrote explanations of evolution using six Darwinian principles: students in he completion condition completed backwards faded, worked-out examples of explanations; students in the problem solving condition wrote full explanations, thought to require means-end problem solving. The dependent variables included the following: a writing task explaining evolution in a novel scenario; an evolution post-test; the number of total principles and target principles, reported difficulty, and perceived effort for each writing activity. The problem solving group demonstrated significantly higher concept transfer compared to the completion group on the evolution post-test, as well as marginally higher concept transfer on the sixth writing task. In addition, the problem solving group included a significantly higher number of total principles over the first four writing tasks. The completion group reported significantly less perceived effort over the first four writing tasks, compared with the problem solving group. Both writing conditions resulted in positive gains between the pre- and post-tests, suggesting that overall, writing-to-learn is effective for teaching evolutionary concepts. It is proposed that writing full explanations using means-end problem solving provides increased task complexity for learners, leading to concept transfer.

Keywords

Causal explanation; writing-to-learn; worked-out examples; schema; completion problem; completion effect; cognitive load.

Dedication

This thesis is dedicated to Dave Paskar, whose love, support and encouragement will be appreciated always.

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Chapter 1

Introduction

Statement of the Problem

Writing-to-learn has been shown to have positive effects on science concept attainment (Bangert-Drowns, Hurley, & Wilkinson, 2004; Hand, Hohenshell, & Prain, 2004; Hand, Wallace, & Yang, 2004; Gunel, Hand, & McDermott, 2009). The effectiveness of writing to learn activities is affected by many contextual factors, including type of prompt (Conner, 2007; Davis, 2003; Furtak & Ruiz-Primo, 2008; Nückles, Hübner, Dümer, & Renkl, 2010; Nückles, Hübner, & Renkl, 2009), type of audience (Gunel et al., 2009; Hand et al., 2004), and the concept involved (Klein, 1999). This study will investigate the characteristics of writing activities that enhance the understanding of the theory of evolution.

Evolution is a difficult subject for students to learn at the secondary level (Engel Clough & Wood-Robinson, 1985; Ferrari & Chi, 1998), yet meaningful understanding of evolutionary concepts is important for the study of biological sciences at the post-secondary level (Alters & Nelson, 2002; Bishop & Anderson, 1990; Engel Clough & Wood-Robinson, 1985; Nieswandt & Bellomo, 2009). Specifically, evolution provides an explanation for biological unity and the diversity of life (Kampourakis & Zonga, 2009). When students are given opportunities to apply Darwin's model of natural selection in order to explain examples of natural phenomena, they gain a more accurate and deeper understanding of the evolutionary process (Kesidou & Roseman, 2002; Passmore & Stewart, 2002; Wilson, 2005). A *causal explanation* is something that identifies the factors or conditions causing a process; these factors or conditions can be manipulated in a way that changes the outcome of what is being explained (Woodward, 2003). In this case, Darwinian theory provides the six factors necessary for the process of evolution: a source of variation; intra-species variation; differential survival rates; a reproductive advantage; an accumulation of genetic change; and overall changes in the population over time. This study seeks to identify effective strategies to teach explanation writing, using the six principles of Darwin's theory.

Worked-out examples are models of step-by-step solutions given to students in order to provide a *schema* that may be stored in long-term memory (Sweller, Ayres, & Kalyuga, 2011). Worked-out examples have been shown to be an effective means by which to teach students how to solve mathematical and physics problems using clearly defined problem-solving algorithms (Renkl & Atkinson, 2010; Sweller et al., 2011). However, there have been a limited number of studies into the effectiveness of using worked-out examples for problems with less clearly defined solution steps (Renkl & Atkinson, 2010), such as for writing an explanation of evolutionary biology. Furthermore, in order to increase attention to the sequence of worked-examples, students can be given a *completion problem*, which is a partially worked-out problem (Sweller et al., 2011). Because students are solving only part of a problem, completing worked-out examples reduces both working memory requirements and mental effort, thereby improving near and far concept transfer.

The *completion effect* with worked-out examples has neither been investigated for written explanations, nor for explanations of complex biological processes such as evolution. The current study investigated the effectiveness of completing worked-out examples of explanation, comprised of the six Darwinian principles, as a teaching strategy to increase evolution concept transfer. Each writing activity comprised a case study of the evolution of a different organism. The completion problems were faded backwards: the first example requires the learner to provide the last step to complete the explanation; the second example requires the student to complete the last two steps; and so on. Students in the experimental condition completed backwards faded worked-out examples, while the comparison group wrote complete explanations for each case. This study measured the effects of backwards faded completion tasks on several dependent variables: a sixth writing task explaining a novel scenario, an evolution post-test, the number of total and target Darwinian principles included in each explanation, reported difficulty, and perceived effort.

Misconceptions Concerning Evolution

According to Samarapungavan and Wiers (1997), children possess explanatory frameworks for describing the origins of life, previous to studying this topic in school. These internally consistent, core sets of beliefs often carry over to adolescent years. Consequently, these schemata conflict with Darwinian theory, when it is taught at the secondary level.

In one common misconception, children may explain evolutionary processes using ideas that are *Lamarckian*. That is, students erroneously believe that individuals spontaneously generate traits in order to adapt to the environment. In addition, students think that these changes happen to the entire population, and not just to the individual (Bishop & Anderson, 1990). This type of thinking is known as *typological* or *essentialist:* adaptation is thought to result from a predetermined “grand scheme” (Engel Clough & Wood-Robinson, 1985; Nehm, Beggrow, Opfer, & Ha, 2012). Children show confusion between adaptive changes occurring during an individual’s lifetime, as compared to population changes that happen over extended time periods (Alters & Nelson, 2002; Bishop & Anderson; Driver, Squires, Rushworth, & Wood-Robinson, 1994). In a second misconception, students use *naturalistic* or *teleological* ideas to explain adaptation: Internal forces instigate morphological changes in response to an organism’s needs, resulting in the individual's overall "improvement" (Deadman & Kelly, 1978; Engel Clough & Wood-Robinson, 1985; Nehm et al., 2012).

Children also demonstrate naïve explanations for the *sources of variation* and the *mechanisms of inheritance*, and often omit ideas explaining *inheritance probability* (Alters & Nelson, 2002; Bishop & Anderson, 1990; Deadman & Kelly, 1978). Because of its intrinsically unobservable nature, some students also consider evidence for evolution, and adaptation in particular, to be invalid or unscientific (Dagher & Boujaoude, 2005). Finally, students show *intentionality* biases: They believe that evolutionary events are directed by some overall intelligence (Nehm et al., 2012). These various misconceptions often carry over from secondary education to the post-secondary level, and affect even high-achieving students majoring in the life sciences (Alters & Nelson, 2002). This last finding suggests that students fail to learn and retain fundamental evolutionary concepts after receiving traditional instruction (lecture and recall) at both secondary and post-secondary levels (Alters & Nelson, 2002; Bishop & Anderson, 1990).

Addressing Student Preconceptions of Evolution

According to Kampourakis and Zogza (2009), previous misconceptions of evolution must be replaced with effective and scientifically sound models. Only then, students may achieve explanatory coherence and conceptual change. Teachers must first identify previous misconceptions (Banel & Ayuso, 2003; Kampourakis & Zogza, 2009), which may include cognitive biases comprising of naïve beliefs about evolution (Kampourakis & Zogza, 2009; Nehm et al., 2012).

In one study, Nehm et al. (2012) examined undergraduate biology students' open-ended, written explanations concerning evolution. The researchers coded the students' writing for two particular features: use of *key concepts* (defined as presence of variation, heritability of variation, differential survival, and differential reproduction rates), as well as *cognitive biases*. The researchers found that 73 percent of students wrote explanations that included both key concepts and cognitive biases: This result confirms the need for students to reflect, address, and reject prior naïve pre-conceptions. Interestingly, the frequency of cognitive biases in explanations was inversely proportional to the frequency of key evolutionary concepts. This result suggests that the explicit teaching of key evolutionary concepts may deter unscientific reasoning when explaining evolution (Nehm et al., 2012).

These findings support the need for a stable mental model, which can be used to create accurate and scientific explanations while discouraging previous misconceptions (Kampourakis & Zogza, 2009; Nehm et al., 2012). The stable mental model of evolutionary explanation may also help to facilitate long-term recall (Opfer et al., 2012). For example, Furtak (2012) describes an effective learning progression based on specific concepts: *variation*, and *differential survival and reproduction,* and mechanisms of *trait prevalence*. In this study, a checklist of these concepts provided common language for both teachers and students. This common language was used to discriminate between key evolutionary concepts and misconceptions. Overall, teaching of Darwinian concepts may scaffold students' explanations of evolution, and may promote the identification and rejection of unscientific ideas.

The Six Key Darwinian Principles

Evolutionary explanations are built with six key principles: *source of variability, intraspecies variability, differential survival rates, reproductive advantage, accumulation of change,* and *changes within a population*. The application of the six key Darwinian principles to novel phenomena can be used to assess students' conceptual understanding of evolution. For instance, Asterhan and Schwarz (2007) measured conceptual understanding using a post-test, which measured the incorporation of Darwinian principles into explanatory schemas. Kampourakis and Zogza (2009) found that application of the principle of *genetic variability* particularly promoted scientific reasoning and conceptual change.

The scientific ideas implicit in the six principles are necessary for writing meaningful explanations of the evolutionary process (Bishop & Anderson, 1990; Deadman & Kelly, 1978), as well as for critical reasoning skills concerning evolution, and avoiding misconceptions (Alters & Nelson, 2002). Previous studies suggest that effective teaching methods promote accurate understanding of the six Darwinian principles. For example, these have included the following: Introducing evolutionary ideas at a much younger age (Engel Clough & Wood-Robinson, 1985); taking account of students' prior conceptions in order to anticipate alternative interpretations (Alters & Nelson, 2002; Deadman & Kelly, 1978; Engel Clough & Wood-Robinson, 1985); asking students to engage in meaningful discussions about their ideas (Alters & Nelson, 2002; Engel Clough & Wood-Robinson, 1985); constructivist approaches, in which students examine their own conceptions in new scenarios; concept mapping; and presenting evolution using historical materials in order to present the creation of the theory of evolution itself as a process, which can provide a model for the development of the student's own conception of evolution (Alters & Nelson, 2002).

Interestingly, even university-bound students fail to incorporate the six Darwinian principles when writing about evolutionary phenomena. For example, Nieswandt and Bellomo (2009) gave Grade 12 biology students written extended response questions based on an evolutionary example (why polar bears are white, or the role of mutation and genetic drift on seal evolution). They found that students often defined key evolutionary terms (such as mutation or genetic drift), but failed to explain or elaborate on these terms in the context of the specific scenario. The authors concluded that students lacked cognitive strategies for linking and transferring knowledge to their written responses (Nieswandt & Bellomo, 2009).

Explicit Cognitive Strategy Instruction to Achieve Explanatory Coherence

The genre of explanation may be taught as a *schema*, or framework, to help students transfer their framework of evolutionary theory to a broad variety of biological concepts. For example, Wilson (2005) suggests teaching a framework of basic principles, which they can use to apply to different biological examples: In doing so, students increase their overall evolution-specific knowledge by using general thinking skills. Consistent application of an explanatory framework between different tasks is known as *explanatory coherence,* and can be used to measure the effectiveness of evolution instruction (Kampourakis & Zogza, 2009).

For example, Passmore and Stewart (2005) had secondary students develop, analyze and elaborate on a specific schema: Darwin's model of natural selection. Students used this model to write narrative explanations for the evolution of particular traits, which were subsequently discussed and critiqued. The researchers found that after these activities, students favoured explanations using Darwin's model over ones that used ideas that were either Lamarckian or based on intelligent design. Students were also able to differentiate between the survival and reproductive advantages for an individual organism and the same advantages for an entire population.

In another study, Sandoval (2003) gave high school biology students "explanation guide" software that suggested useful prompts for constructing evolutionary explanations. Specifically, each explanation guide provided three key prompts: a specific theoretical framework of evolution or ecology; instructions on how to write coherent, supported explanations; and hints about how to link evidence from their scientific investigation to their explanations. After being presented with an inquiry problem, students were asked to write explanations of natural selection for a scenario involving the Galapagos Islands finch populations. Sandoval (2003) found that the students' explanations were more articulate after they wrote investigation journals using software support. Moreover, students receiving computer prompts wrote with more causal coherence and included a greater number of explanation elements. Students also participated in numerous group discussions of the explanation genre.

Cognitive Load Theory

In the previous section, it was shown that instruction in writing evolutionary explanations of novel phenomena contributed substantially to students' understanding of evolutionary principles. Nonetheless, learning to write evolutionary explanations is challenging. In recent research on complex learning, cognitive load theory has been instrumental.

Types of cognitive load. When something new is learned, the total *cognitive load* is the sum of two components: intrinsic cognitive load, which is imposed by the information itself that is required to achieve learning goals; and extrinsic cognitive load, which is imposed by instructional methods and does not contribute to learning goals. Total cognitive load can be measured by mental effort and difficulty (Sweller et al., 2011).

According to the *cognitive load theory,* the primary purpose of instructional design is to facilitate the construction of schemata in long-term memory. This is achieved by presenting information in a manner that reduces extraneous load, while maintaining intrinsic load at a moderate level. This allows the student to complete the specific task at hand, and to abstract the underlying schema. Therefore, instructional design is most effective when it reduces extraneous resources that demand working memory (Sweller et al., 2011).

Schema acquisition. As noted above, learning is comprised of the acquisition of *schemas*. Schemas consist of multiple elements that are connected to form relationships. (Sweller et al., 2011). Schemas are constructed when the relationships among elements of the schema are processed in working memory. This requires that the student direct attention to one sub-goal or concept at a time as the schema is applied to a problem.

For example, the six Darwinian principles are related, interacting elements – more than one principle must be processed simultaneously in order to write an effective explanation. Learners must familiarize themselves with the *relationships* among the principles: For example, the learner must invoke the principle of *source of variation*, and then connect this to the principle of *intra-species variability* in a population. The high interactivity between the principles requires increased working memory resources and therefore imposes high intrinsic cognitive load (Sweller et al., 2011). Ultimately, once this explanation schema is stored in long-term memory, it can be retrieved as a single element or "chunk" (Sweller et al., 2011). Thus, writing evolutionary explanations based on this schema could potentially minimize the total working memory and extraneous cognitive load, and increase the accurate learning of concepts.

Traditional problem solving imposes extraneous cognitive load. Sweller (1988) theorized that learning through problem solving involves two tasks, one primary and one secondary. In the primary task, the student is attempting to solve the actual problem at hand. For example, for a problem asking a student to solve a mathematical equation, two numbers are added together when he or she sees that there is an addition sign between them. The secondary task involves both acquiring knowledge of the problem structure, and acquiring knowledge of useful elements that will help to solve future, similar problems. For example, when solving equations, the student learns that he or she is only supposed to add two numbers together after all multiplication steps have been completed first.

Traditional teaching of mathematical problem solving frequently requires means-end problem solving. This is a strategy often employed by novice learners. Because novice learners lack appropriate schemata for solving a given type of problem, they instead resort to means-end analysis, which requires them to identify a goal, and work backward to derive subgoals from it (Sweller, 1988). For example, for a math equation, a student using means-end problem solving may have a specific goal of simplifying the expression from four terms to one. Means-end problem solving is highly inefficient because the problem solver must deal with several interacting elements at once: the current problem solving state (four terms), the goal state (equation simplified to one term), the relationship between problem solving operators, and new subgoals as they are derived (Sweller, 1988). These interacting elements require high levels of working memory and extrinsic cognitive load, leaving fewer cognitive resources for the secondary task of schema acquisition, that is, learning how to solve the problem. .

Using worked-out examples to reduce extraneous cognitive load. *Worked-out examples* provide the learner with step-by-step solutions to a problem (Sweller et al., 2011). A worked-out example includes a problem formulation, steps to the solution, and the final solution (Renkl & Atkinson, 2010). Worked-out examples eliminate the need for means-end problem solving, reducing the cognitive load on the learner, and the errors that result from using such strategies (Sweller & Cooper, 1985).

Worked-out examples provide useful information required for the secondary task of schema acquisition. For example, the worked-out example helps learner to understand the relationship between different problem states, and to identify relevant moves towards solving the problem (Sweller & Cooper, 1985). Additionally, because the extraneous load of means-end problem solving is reduced, the learner can redirect attention to learning and processing novel information. The study of worked out examples has been found to be effective in several experiments: Worked-out examples have a positive effect on learning accuracy and efficiency (Carroll, 1994), and can reduce mental effort, leading to a greater retention and near-transfer of concepts (Kyun, Kalyuga & Sweller, 2013; Richey & Nokes-Malach, 2013).

The completion effect and transfer of concepts. Previous research on solving algorithmic problems has shown that worked-out examples may be made more effective by fading the example as students complete successive practice problems, so that difficulty is gradually increased (Renkl, Atkinson, Maier, & Staley, 2002). The following progression exemplifies the backwards fading of a *completion problem*: In a schema with six steps, all six steps would first be presented as a worked-out example. The next worked-out example would present the first five steps; when the student generates proficiency in completing this step, the next type of practice problem would be introduced, in which the final two steps are removed, and so on. It is thought that backwards fading helps increase prompt efficiency in two ways: by reducing the time spent on studying worked-out examples, while maintaining ability to transfer strategies to future tasks; and by reducing overall extraneous cognitive load.

In their first of two experiments, Renkl, Atkinson, and Maier (2000) investigated the *completion effect* with two ninth grade physics classrooms learning how to solve three-step electricity problems. The experimental classroom was asked to complete worked-out examples that were faded *backwards*: first, the complete three-step solution was given, and one step was removed in each subsequent task until no steps were given. On the other hand, the comparison, or problem solving group, received example problem-pairs without any worked-out examples. The study showed that students completing backwards faded, worked-out examples scored higher in both the near and far-transfer post-tests, compared to the problem solving students (Renkl et al., 2000). In the second experiment, university psychology students learned concepts of probability using a computer-based program (Renkl et al., 2000). The participants were assigned to either a completion group receiving *forwards* faded worked-out examples, or a problem solving group receiving example problem pairs. For the experimental group, the first task was to study a completed, worked-out example; subsequent tasks removed the first solution step, then the second, and so on. The problem solving group received example-problem pairs for all tasks. The completion group scored higher on the near transfer post-test and demonstrated greater correctness in solution steps; however, the completion group scored lower in the far-transfer test, compared with the problem solving group. Therefore, the completion effect may foster learning and near-transfer, but not necessarily far-transfer (Renkl et al., 2000).

Another study by Baars, Visser, Gog, Bruin, and Paas (2013) investigated the effects of removing the middle steps of completion problems; effects were measured for judgments of learning and mental effort. In this study, students were asked to complete a six-step heredity problem: the fourth and fifth steps were removed. Students completing these examples – where the middle steps were removed – demonstrated decreased judgements of their own learning as well as increased mental effort, compared to students who received fully worked-out examples. The findings from the forwards fading experiment (Renkl et al., 2000) as well as the experiment removing the middle steps of the completion problem (Baars et al., 2013), suggest that backwards fading may be most effective for far-transfer of concepts, compared with either forwards or middle fading. Additional studies have examined the conditions for the effectiveness of the completion method (Salden, Aleven, Schwonke, & Renkl, 2010).

Therefore, the manner with which worked-examples are presented to learners needs to be further investigated, in order to maximize their effectiveness in specific educational contexts, such as in evolutionary biology. Previous studies suggest that backwards fading may be most effective for the transfer of concepts, compared with forwards or middle fading (Baars et al., 2003; Renkl et al., 2000; Renkl et al., 2002). Backwards fading allows the last step to be removed first, thus preventing the extraneous cognitive load that may result from the learner having to generate the first step during the primary task (Renkl et al., 2002; Sweller et al., 2011).

Incorporating self-explanation prompting into worked-out examples. When worked examples are faded *and* supplemented with self-explanation prompting, the effects are additive (Renkl & Atkinson, 2010). Specifically, self-explanation prompts encourage learners to use freed cognitive capacity to explain the steps to a given example, thus increasing their knowledge of the schema (Renkl & Atkinson, 2010). Indeed, think-aloud prompts help reduce unproductive learning events and increasing learning outcomes (Sweller et al., 2011). Incorporating self-explanation prompts into backwards-faded examples also optimizes achievement on both near and far-transfer tasks, as opposed to using backwards fading only (Renkl & Atkinson, 2010).

Evolution is a complex schema involving abstract Darwinian principles. The understanding of the Darwinian principles is necessary for accurate evolutionary explanations. Without a precise understanding of the mechanisms driving evolution, students lack the foundation for understanding important biological principles (Alters & Nelson, 2002; Bishop & Anderson, 1990; Engel Clough & Wood-Robinson, 1985; Nieswandt & Bellomo, 2009). As a single strategy, writing entire evolutionary explanations has not proven to be an effective teaching method for increasing conceptual understanding (Asterhan & Schwarz, 2007; Nehm et al., 2012; Nieswandt & Bellomo, 2009). Therefore, this study seeks to investigate if backwards faded, worked-out examples, as completion problems, can reduce extraneous cognitive load and promote the acquisition of evolutionary schemas. Many past studies have investigated the effectiveness of worked-out examples for mathematical or scientific calculations (Carroll, 1994; Renkl et al., 2000; Richey & Nokes-Malach, 2013; Sweller et al., 2011; Sweller & Cooper, 1985), but not for writing-to-learn. Therefore, this study investigates if the positive effects of worked-out examples extend into biology for writing explanations of evolutionary processes.

Hypotheses

1. Completion of worked-out examples of explanations, compared to problem solving to write complete explanations, produces higher scores on a final writing task when students are asked to transfer knowledge to a novel situation.
2. Completion of worked-out examples of explanations, compared to problem solving to write complete explanations, produces higher scores on the transfer of concepts in an evolution post-test.
3. Completion of worked-out examples of explanation, compared to problem solving to write complete explanations, produces more inclusion of the six key Darwinian principles during the writing tasks.
4. Completion of worked-out examples of explanations, compared to problem solving to write complete explanations, produces lower cognitive load, as measured by Likert scale self-reported difficulty for each writing activity.
5. Completion of worked-out examples of explanation, compared to problem solving to write complete explanations, produces lower cognitive load, as measured by Likert scale self-reported effort for each writing activity.

Chapter 2

Method

Research Design Overview

A pre-test post-test quasi-experimental design examined the effects of completing backwards faded, worked-out examples, compared with problem solving in order to write evolutionary explanations. The evolution pre-test and post-test were designed to measure domain-specific knowledge of evolutionary concepts. The lesson sequence included six writing tasks, during which students learned to write explanations for various novel evolutionary phenomena (Appendix F). For these six tasks, the completion group was asked to complete worked-out examples of explanations, which were faded backwards. The problem solving group was asked to write complete explanations for all tasks. The sixth writing task asked students in both groups to complete a full explanation of a novel phenomenon (Appendix F). For each writing activity, students were asked to self-report their effort and the perceived difficulty of the task.

Participants

Participants included 52 students from four classes of Grade 11 university-level biology students from an inner-city secondary school of the Toronto District School Board. Grade 11 university-level biology classes with enriched science students were excluded from participating, in order to reduce possible pre-existing achievement differences within the study population. Each of the regular-stream biology classes was randomly assigned to a treatment condition: Two were assigned to the problem solving condition (problem solving to write full explanations) and two were assigned to the completion condition (completion of backwards faded worked-out examples). In order to obtain free and informed consent from each Grade 11 student, a teacher from the school's math department visited each of the four biology classes at the beginning of each semester. The teacher explained the study to students and provided informational letters and consent forms. The teacher collected consent forms and kept them until the end of each semester, after all final grades were distributed. In this way, the identities of the participants were kept confidential from the researcher and classroom teachers during the course of the study.

All instruments and consent forms were collected and secured in the science department office at the school: Only the researcher had access to these files. These instruments remained in this secure location for the duration of the study.

Procedure

Curriculum context. Several measures in the protocol ensured that the conditions of the two classes were kept the same. Both teachers were expected to deliver very comparable unit lessons, because they were both familiar with the Grade 11 university-level biology curriculum (Ontario Ministry of Education, 2008). Before the study began, both teachers had taught multiple semesters of the evolution unit and its accompanying activities. One teacher was the researcher. One teacher taught one class in the completion condition; the other teacher (also the researcher) taught one class in the completion condition, and two classes in the problem solving condition. Specifically, in the first year of the study, two different teachers taught each of the two treatment classrooms. In the second year, one of those two teachers (the researcher) taught both treatment groups, due to teacher timetable and scheduling restraints.

Given these circumstances, all lessons, writing instruction, and writing tasks were outlined in great detail (Appendices C, D, E and F). Other than the experimental intervention, all aspects of content and method of instruction between the classes were kept the same: Reading material and assignments, lectures, practice problems, and feedback on practice problems were all comparable between conditions.

Firstly, detailed outlines of the focal lesson (Appendix C) were given to both teachers, as well as the checklist of the six Darwinian principles (Appendix E). This information was provided to ensure that both treatment groups received the same guidelines for writing. Secondly, a detailed thirteen-day lesson sequence checklist (Appendix D) provided both teachers with guidelines for the exact textbook pages for lecture content and student readings. This resource also included a day-by-day checklist, indicating the exact writing tasks, student activities, and questionnaires to be delivered. Thirdly, writing tasks for both completion and problem solving groups (Appendix F) were distributed in the same manner for each group. Because the researcher was one of the teacher participants, detailed outlines were necessary to ensure consistency between treatment groups.

Pre-testing. Students completed a pre-test on evolutionary concepts (Appendix A or B) before lessons or writing tasks were given. The pre-test measured students' pre-existing, domain-specific knowledge of evolution. Scores provided a baseline for measuring possible gains. One half of the class received Form A (Appendix A), and the other half received Form B (Appendix B). Form A and B were also used as the post-test: Each participant received the alternate forms for their pre-test and post-test (Appendix A and B). The pre-test and post-test both contained one short answer question, which asked students to explain natural selection, as well as seven, two-tiered multiple choice questions concerning evolutionary phenomena. Each student received a score out of 20: six for the short answer component, and 14 for the multiple-choice component.

Focal lesson to introduce six Darwinian principles and two fully worked examples. Both completion and problem solving groups received a focal lesson introducing the six Darwinian principles used to explain evolutionary processes: *source of variability, intraspecies variability, differential survival rates, reproductive advantage, accumulation of change,* and *changes within a population.* Students in each class read articles describing the evolution of two biological phenomena (Appendix G). Then, students analyzed two fully worked examples of explanation: Each explanation included all six Darwinian principles (Appendix C). Students were asked to identify the principle that corresponded to each part of the example. As a reflection activity, classroom teachers asked students to “write two paragraphs, one for each phenomenon, paraphrasing the evolutionary concepts” for each worked-out example. Students then shared their ideas in a think-pair-share activity, as a way of prompting and checking that students read and thought about each step of the two worked-out examples.

The researcher posted a list of the six Darwinian principles at the front of each classroom, so that it was visible to all students of both conditions during the focal lesson and the six writing tasks (Appendix E).

Lessons to teach curriculum on evolution. After the focal lesson, students in both groups received lessons on evolution, designed to teach the expectations of the provincial science curriculum (Ontario Ministry of Education, 2008). In order to ensure comparable lesson deliveries, the researcher met with the other classroom teacher to review the lesson sequences, concepts and activities. Specifically, each classroom teacher used a common checklist of required lesson characteristics, which each teacher confirmed was applied to both treatment groups (Appendix D).

The first lesson (day 1) focused on early ideas about evolution, in accordance with the class textbook (Ellis, Muller, Panayiotou, Sharp, & Webb, 2011, pp. 187-189). In this lesson, students received a lecture and wrote notes about evidence for evolution, the age of the earth, and the ideas of Charles Lyell, Thomas Malthus, and Jean Baptiste Lamarck. Students were then asked to complete textbook questions and a vocabulary activity of their choice.

The second lesson (day 3) focused on Darwin's observations as well as the development of his theory, in accordance with the class textbook (Ellis et al., 2011, pp. 189-194). In this lesson, students received a lecture and wrote notes about Darwin's voyages, his principle observations of species characteristics, and how his theory developed. Students were asked to complete textbook questions, and also to watch a video called *Origin of Species: Beyond Genesis* (Killeen, Ward, & Sutherland, 2005). This video reviewed Darwin's career, his findings, and the impact his ideas had on scientific thinking at the time.

The third lesson (day 5) focused on Darwin's model of natural selection, in accordance with the class textbook (Ellis et al., 2011, pp. 195-199). Students received a lecture and wrote notes on several concepts: descent with modification; the struggle for existence; variation; the role of the environment; and the theory of natural selection. Students were asked to complete textbook questions, and also watched a video called *Charles Darwin and the Tree of Life* (BBC Natural History Unit, 2009).

The fourth lesson (day 7) focused on the evidence for evolution on which Darwin built his theory of natural selection. Students took notes on a lecture based on the classroom textbook (Ellis et al., 2011, pp. 199-204) about the following concepts: the fossil record; geographic distribution; homologous structures, vestigial structures, and analogous structures; comparative development; and molecular biology. Students were asked to answer textbook questions, as well as complete an Active Folder called *Adaptations* (Glencoe Education, 2006).

The fifth lesson (day 9) focused on the concept of artificial selection, and how it serves as evidence for Darwin's theory of natural selection. Students took notes on a lecture based on the classroom textbook (Ellis et al., 2011, pp. 205-208). This lesson also covered other examples in biology that serve as evidence for evolution (changes in beak shape in finches, antibiotic resistance in bacteria). Students were asked to answer textbook questions and to complete an online simulation Gizmo about evolution, called *Evolution: Natural and Artificial Selection* (ExploreLearning, 2012).

The sixth lesson (day 11) focused on the concept of genetic variation as well as sexual selection, and covered several concepts: variation in gene pools; the roles of mutation and sexual recombination; microevolution; genetic drift; the bottleneck effect; the founder effect; and gene flow. Students took notes on a lecture based on a section of the classroom textbook (Ellis et al., 2011, pp. 212-221). As a follow up to this lesson, students were also asked to complete textbook questions as well as an online simulation Gizmo about evolution, called *Evolution: Mutation and Selection* (ExploreLearning, 2012). The purpose of this Gizmo was to observe a fictional population of bugs, set the background habitat colour to different settings, and observe the natural selection process.

Finally, in the seventh lesson (day 13), students completed an inquiry activity, based on industrial melanism and the peppered moth. For this activity, all students chose to complete another Gizmo about evolution, called *Natural Selection* (ExploreLearning, 2012). In this Gizmo, students participated in a virtual simulation of birds hunting dark and light-coloured moths. Students preyed on and "killed" highly visible moths, thus allowing most of the camouflaged moths to survive. As a result, students observed accumulations of change and changing populations over time. This inquiry activity was marked for the purpose of the student's class grade.

Writing tasks. On each second day, alternating with lesson days (i.e., days 2, 4, 6, 8, 10 and 12), students in both classes participated in writing tasks. The completion group received faded, worked-out examples; the problem solving group was asked to write full explanations

(Appendix E). For each writing activity, students in both treatments were given a newspaper or magazine article describing a specific biological phenomenon (e.g., antibiotic-resistant bacteria, dwarf elephants; Appendix G). In this way, each writing activity included a source describing the environmental context, as well as the trait that evolved in this context. Students were asked to explain the biological phenomenon, using Darwin's six principles (Appendix F). Thus, the source materials did not provide an explanation of the evolution of a given trait, but they provided information that would allow students to construct an explanation of the trait, through the application of Darwinian principles. During the writing tasks, students in both the completion and problem solving classes were able to see a classroom poster listing the six Darwinian principles (Appendix E). Both the completion and problem solving classes were asked to complete a reflective activity after each writing task, labelling each part of their explanation with the correct Darwinian principle (Appendix F).

Recall that during the focal lesson, students received two fully worked-out examples, each including all six steps of an explanation. Each step of the explanation applied of one of the six Darwinian principles: *source of variability, intra-species variability, differential survival rates, reproductive advantage, accumulation of change,* and *changes within a population*. For the writing activities, the completion group received worked-out examples of explanation, which were faded in a backwards manner. After the first evolution lesson (day 1), completion students received the first completion task (day 2), which included a backwards-faded worked-out example with the last solution step (*changes within a population*) removed. Completion students completed the explanation by writing about the last Darwinian principle in context of the evolutionary phenomenon. After the second evolution lesson (day 3) completion students received another evolution article and their second completion task (day 4), which included another worked-out example with the last two solution steps removed (*changes within a population*, and *accumulation of change*). Completion students were then asked to write about the missing two Darwinian principles in the context of the evolutionary phenomenon. For the next four writing tasks (days 6, 8, 10 and 12), completion students asked to complete tasks with additional steps removed (see Appendix D and Appendix F).

Students in the problem solving group were asked to write explanations for the same evolutionary phenomena as the completion group. However, the students in the problem solving group completed all six writing tasks without worked-out examples or steps. Specifically, problem solving students received a blank response sheet and were instructed only to "explain the evolution behind the phenomena you have read about, using Darwinian principles."

For the sixth and final task, concerning the evolution of mussels, students in the both completion and problem solving groups were required to write an entire explanation that included all six principles.

Students submitted their writing tasks to the teacher, who forwarded these to the researcher. For both groups, the researcher read the writing tasks and provided written feedback, based on the assessment checklist of Darwinian principles (Appendix E). In the beginning of the next class, the classroom teacher provided this written feedback to the student, as well as their score for the particular writing task.

The student's score for each completion task was recorded in two ways: the total number of principles added, and total number of *target* principles added. For the total number of principles added, each student received one mark for each Darwinian principle in their explanation, regardless of which principle it was. For the total number of *target* principles added, each student received one mark for each target Darwinian principles included in their explanation:

The target principle or principles depended on the number of the writing task. For example, for the first writing task, the target Darwinian principle was the last step of the explanation *(changes within a population)*. For the second writing task, the target Darwinian principles were the last two steps (*accumulation of change* and *changes within a population*). For the third writing task, the target Darwinian principles were the last three steps *(reproductive advantage, accumulation of change,* and *changes within a population)*, and so on. Because the worked-examples were faded in a backwards manner, the target principles increased by one for each subsequent writing task.

Likert scale questionnaires. Each student received six questionnaires: one after each writing task. Each questionnaire featured two Likert scales: one measured students' self-reported difficulty, and the other measured their self-reported effort for each writing task (Appendix H).

Sixth writing task assessment. The sixth writing task (day 12) served as an immediate assessment of transfer of evolutionary concepts. Students in both groups were asked to write about a novel scenario – the evolution of mussels' thick shells – using all six Darwinian principles. This writing task was identical for students in both conditions. The sixth writing task was evaluated using the assessment checklist (Appendix E).

Evolution post-test. Seventeen days after day 13, students in both groups received a post-test, which assessed the transfer of evolutionary concepts (Appendix A or B). Like the pre-test, the post-test contained one short answer question, which asked students to explain natural selection. The post-test also included seven, two-tiered multiple choice questions asking about explanations for various evolutionary situations. Each student received a score out of 20: up to six points for the short answer component, and up to 14 points for the multiple-choice component. Students who received Form A as a pre-test received Form B as a post-test, and vice versa.

Materials and Assessments

Pre-test (Appendix A or B) to assess prior knowledge and to measure baselines. The design of the test was informed by previous research on students' understanding of evolution (Asterhan & Schwarz, 2007; Nieswandt & Bellomo, 2009). Questions were designed to address each aspect of the evolutionary process. The first section included a short *written response*, in which students were asked to respond to one of two questions about natural selection: either "Explain how living things change over generations" (Appendix A), or "How do organisms evolve?" (Appendix B). The written response was worth six marks, and was evaluated using the checklist of Darwinian principles (Appendix E).

The second section was a *multiple-choice* assessment consisting of seven, two-tiered multiple-choice questions (worth 14 marks total). In a two-tiered multiple choice question, the first part of each question required the student to select an answer, and the second part of each question required them to select a justification for the first answer. Within each question, one alternative represented the standard, scientific understanding of evolution; other alternatives represented common misconceptions about evolution. According to Alters and Nelson (2002), multiple-choice assessments are both reliable and effective for the assessment of evolutionary concepts when common misconceptions are provided as "distracters," as they were for the pre- and post-tests. Overall, both pre- and post-tests (Appendix A and B) were worth 20 marks each.

In order to determine initial class differences, the researcher obtained scores from a pre-test measuring pre-existing, domain-specific knowledge on evolution (Appendix A or B). This assessment was completed before the lessons and writing tasks were given. Inter-item reliability was determined for Form A and Form B. Students completing pre-test Form A had comparable mean scores, $M = 8.09$, $SD = 1.69$, to the students completing pre-test Form B, $M = 8.05$, $SD =$

3.09. However, pre-test form A showed an unacceptable inter-item reliability (α = -0.08), while pre-test form B showed a poor inter-item reliability (α = 0.56). This was thought to be because of poor scores for the second parts of the multiple-choice questions, which primarily involved explanations of evolution on a population level (Appendix A and B). In particular, questions 2b and 3b from pre-test form A, as well as question 8b from pre-test form B, did not correlate with pre-test totals. (It will be argued below that the low inter-item reliability of the pre-tests was not the result of poor design, and instead indicated the ubiquity of misconceptions about evolution in the sample of students, prior to instruction.)

All pre-tests were graded by the researcher. In addition, a random sample of short-answer responses from the pre- and post-tests were graded by another rater, in order to calculate inter-rater reliability. For the other rater, it was masked as to whether the explanation was a pre-test or post-test, and whether the participant was from the completion or problem solving group. The inter-rater reliability for scores of the pre- and post-tests was found to be excellent (α = 0.95).

In order to determine test-retest reliability, total scores from the pre-test were correlated with total scores from the post-test. The test-retest reliability was found to be low (α = 0.19), indicating low repeatability. It was inferred that because instructional treatments occurred between the pre-test and post-tests, test-retest reliability was low.

Evolution post-test (Appendix A or B). Seventeen days after the last lesson (day 13), a post-test was used to assess the transfer of evolutionary concepts. Students received either Form A or B: the alternative to what was given for the pre-test (Appendix A and B). Inter-item reliability was determined for both Form A and Form B. Students completing post-test Form A had lower mean scores, M = 10.77, SD = 3.22, compared to the students completing post-test Form B, M = 13.55, SD = 3.60. Reliability for post-test forms was unacceptable for test form A (α = 0.46) but acceptable for test form B (α = 0.63). The low reliability for post-test A resulted from question 8b in particular, which did not correlate with totals for post-test A marks.

All tests were graded by the researcher. As previously described, a random sample of written responses from pre- and post-tests were graded by another rater. This was done in order to measure inter-rater reliability for the pre- and post-tests, which was excellent (α = 0.95).

Sixth writing task assessment (day 12). In the sixth writing task, students in both completion and problem solving groups were provided with a source describing a novel environmental context and evolved trait. They were asked to write a full explanation of the evolution of the trait, using the six Darwinian principles. Therefore, the worked-out example was faded completely and removed, but both groups were still cued to include six principles on the response sheet (Appendix F). This required students to construct an original explanation using the six principles, which was not provided by the source materials.

The sixth writing task was worth six marks and was evaluated by the researcher using the checklist of Darwinian principles (Appendix E). Students were given a score of 0 or 1 for each Darwinian principle that was discussed in context of the phenomenon under consideration. In addition, all sixth writing tasks were graded by another rater, in order to measure inter-rater reliability. For the rater, it was masked as to whether the writer was in the completion or problem solving group. The inter-rater reliability was found to be very good (α = 0.83).

Number of added Darwinian principles in students' compositions. In order to measure learning gains over the first four writing tasks, the total number of added principles was measured for both groups. "Added" principles refer to those written by the student; for the completion condition, this meant principles that were not provided already in the partially completed explanation.

In addition, the total number of target principles for each writing task was measured. Target principles refer to those principles that students in the completion condition were expected to add at a given step of instruction. For example, for both groups, the number of target principles in the first task was one. In the second task, two target principles were measured; in the third task, three target principles were measured, and so on. These measurements served as formative assessment of the learning occurring during completion tasks for the completion group. This allowed for the fact that in each writing task, the maximum number of principles that could be added was limited in the completion condition.

Likert scale questionnaires measuring difficulty ratings and perceived effort. Each student (in both completion and problem solving groups) received a questionnaire following each writing task. The questionnaires were based on two Likert scales, indicating the relative difficulty, or cognitive load, of writing completion tasks or explanations (Appendix E). The first Likert scale measured self-reported difficulty, using a nine-point scale that ranged from “very, very easy” (score of 9) to “very, very difficult” (score of 1). The second Likert scale measured the self-reported perceived effort exerted during the completion tasks. It also used a nine-point scale, that ranged from “very, very little effort” (score of 1) to “very, very much effort” (score of 9) (Kyun et al., 2013; Pollock, Chandler, & Sweller, 2002). .

Analysis

The Statistical Package for the Social Sciences, Version 20, was used for all analyses. An independent samples t-test was used to compare the pre-test means of the two groups. A paired-samples t-test was also performed to compare pre- and post-test scores.

Due to individual student absences or individual students not completing specific items (e.g., writing tasks or Likert scales), some data was missing. The first step in dealing with missing data is that students who did not complete the evolution post-test were considered not to have completed the study, and were dropped from the analysis. This resulted in dropping four students.

The second step in dealing with missing data focused on the practice writing activities. 46 of the remaining 48 students completed at least four of the five practice writing activities; however, only 32 of the 48 students completed all five practice activities. This would mean that for statistical procedures that involve list-wise deletion of cases from analysis (e.g., repeated measures), a considerable number of cases could have been dropped from the analysis. Consequently, to prevent this, the analysis of the practice writing activities focused on the first four writing activities completed by each individual student. That is, if a given student completed four activities, these were the focus of analysis; if a student completed five practice activities, then the first four comprised data for analysis.

The third step in dealing with missing data involved imputation. Due to individual absence or non-response to some items, usually Likert scales, two students were missing individual data points. The total percentage of missing data at this stage was less than one percent. To address these missing data points, the SPSS single imputation procedure was performed using the regression procedure.

A one-way analysis of variance (ANOVA) was used to determine the effect of the writing condition (completion versus problem solving) on scores for the sixth writing task assessment. A one-way ANOVA was also used to determine the effect of the writing condition (completion versus problem solving) on scores of the evolution post-test.

A repeated measures ANOVA was used to determine the effect of the writing condition (completion versus problem solving) on the total number of principles added to first four writing tasks completed by each student. (See the note on missing data). For total number of principles, students scored one point for any Darwinian principle discussed in context of the phenomenon. Another repeated measures ANOVA was used to determine the effect of the writing condition (completion versus problem solving) on the total number of target principles added for the first four writing tasks completed by each student. A repeated measures ANOVA was also used to determine the effect of the writing condition (completion versus problem solving) on the reported difficulty for the first four writing tasks completed by each student. Finally, a repeated measures ANOVA was used to determine the effect of the writing condition (completion versus problem solving) on perceived effort for the first four writing tasks completed by each student. For all repeated measures ANOVAs resulting in significant results, planned comparisons were conducted in order to describe within-group trends of the dependent variables.

Chapter 3

Results

Analysis

Data screening and preliminary calculations. A Levene's test did not find significant differences in population variances between the completion group and the problem solving group, $p > 0.05$. A one-sample Kolmogorov-Smirnov test confirmed a normal distribution. An independent samples t-test did not find statistically significant differences between the mean pre-test total score of the completion group, $M = 8.52$, $SD = 2.78$, and the problem solving group, $M = 7.88$, $SD = 2.09$, $t(45) = .908$, $p = 0.37$ (Table 1).

Table 1.

Summary of Means and Standard Deviations for Pre-test Scores

Treatment	N	Pre-Test (max = 20) *M (SD)*
Completion	16	8.52 (2.78)
Problem solving	32	7.88 (2.09)

Note. p<.05 are in boldface.

Paired-samples t-test to determine pre-test post-test differences. A paired t-test was performed for all of the participants to determine whether there was a statistically significant mean difference between pre-test and post-test scores after the instructional treatments (completing worked-out examples or problem solving). The paired t-test found a significant difference between the scores of the pre-test, $M = 8.09$, $SD = 2.33$, and scores of the post-test, $M = 13.63$, $SD = 3.47$, $t(47) = -9.900$, $p < 0.001$ (Table 2).

Table 2.

Summary of Means and Standard Deviations for Pre-test and Post-test Scores

Measure	N	Score (max =20) *M (SD)*
Pre-test	48	**8.09 (2.33)**
Post-test	48	**13.63 (3.47)**

Note. p<.05 are in boldface.

ANOVAs for sixth writing task and evolution post-test. Recall that the first hypothesis stated that the completion of worked-out examples of explanations, compared to problem solving to write complete explanations, would produce higher scores on the sixth writing task, when students are asked to transfer knowledge to a novel problem. A one-way analysis of variance (ANOVA) was conducted to determine the effect of the treatment condition on scores from the sixth writing task. The ANOVA found marginally significant differences between the mean scores of the completion group, $M = 3.12$, $SD = 2.09$, and the problem solving group, $M = 4.22$, $SD = 1.85$, $F(1, 46) = 3.47$, $p = 0.07$, partial $\eta^2 = 0.07$. Therefore, the first hypothesis was rejected; that is, completion of worked-out examples of explanation, compared to problem solving, did not produce higher scores in the sixth writing task, which assessed transfer of concepts. Instead, the results suggest that problem solving to write complete explanations may increase knowledge transfer, compared with completion of worked-out examples.

The second hypothesis stated that the completion of worked-out examples of explanations, compared to problem solving to write complete explanations, would produce higher scores on the transfer of concepts to an evolution post-test. A one-way ANOVA was conducted to determine the effect of the treatment condition on evolution post-test scores. The completion group scored significantly lower on the post-test, $M = 12.13$, $SD = 3.05$, compared with the problem solving group, $M = 14.38$, $SD = 3.46$, $F(1, 46) = 4.86$, $p = 0.03$, partial $\eta^2 = 0.10$. Therefore, the second hypothesis was rejected. Instead, problem solving to write complete explanations produced higher evolution post-test scores, compared with completion of worked-out examples.

Repeated measures ANOVAs for the first four writing tasks. Four ANOVAs were performed, in which the dependent variables were measures of the quality of explanations (operationalized as the number of total or target Darwinian principles), or measures of cognitive load (operationalized as reported difficulty or perceived effort). The repetition of the measures was represented by a "time" variable. For significant results, planned polynomial contrasts were performed in order to determine data trends.

The third hypothesis stated that the completion of worked-out examples of explanation, compared to problem solving to write complete explanations, would produce more inclusion of the six key Darwinian principles during the writing tasks. A repeated measures ANOVA was performed on scores for the total number of principles added for the first four writing tasks. Mauchly's test confirmed sphericity of the paired variables ($p > 0.05$). The repeated measures ANOVA found significant between-group differences for the total number of added principles, $F(1, 46) = 10.89$, $p = 0.00$, partial $\eta^2 = 0.19$. In particular, the completion group added a significantly lower number of total principles over the first four writing tasks, compared to the problem solving group (Table 3). The ANOVA also found significant within-group effects of time on the total number of added principles, $F(3, 138) = 31.44$, $p = 0.00$, partial $\eta^2 = 0.41$. The polynomial planned contrast showed that this trend was significantly linear, $F(1, 46) = 78.81$, $p < 0.001$, partial $\eta^2 = 0.63$, and that the rate of growth of the differences between groups was linear, $F(3, 138) = 3.12$, $p = 0.03$, partial $\eta^2 = 0.06$. In addition, the completion group demonstrated more rapid gains in the total principles added over time, compared to the problem solving group, $F(1, 46) = 8.05$, $p = 0.01$, partial $\eta^2 = 0.15$.

Consequently, the third hypothesis was rejected: Completion of worked-out examples of explanation does not produce more inclusion of the six key Darwinian principles during the writing tasks compared to problem solving. Instead, students who used problem solving included significantly more of the six key Darwinian principles during the first four writing tasks. Additionally, participation in the first four writing tasks elicits a statistically significant within-group increase in total number of principles. The rate of growth of the differences between groups was linear, with the completion group demonstrating more rapid gains over time.

Table 3.

Mean Total Number of Principles Added for First Four Writing Tasks

Treatment	N	Time 1	Time 2	Time 3	Time 4
			M (SD)		
Completion	16	0.50 (0.52)	1.00 (0.89)	2.13 (1.31)	2.75 (1.57)
Problem solving	32	2.62 (1.90)	2.69 (1.89)	3.41 (1.97)	3.74 (1.90)

The third hypothesis was that completion of worked-out examples of explanation, compared to problem solving to write complete explanations, would produce more inclusion of the target Darwinian principles during each writing task. A repeated measures ANOVA was performed on scores for the number of target principles added for the first four writing tasks. Mauchly's test confirmed sphericity of the paired variables between completion and problem solving groups ($p > 0.05$). The repeated measures ANOVA did not find significant between-group differences for the number of target principles added, $F(1, 46) = 0.69$, $p = 0.41$, partial $\eta^2 = 0.02$.

However, the ANOVA found significant within-group differences for the effects of time on the number of target principles added, $F(3, 138) = 69.78$, $p < 0.001$, partial $\eta^2 = 0.60$. Moreover, the polynomial planned contrast confirmed a significant linear trend, $F(1, 46) = 128.81$, $p < 0.001$, partial $\eta^2 = 0.74$, but there was no significant growth of differences between groups, $F(3, 138) = 0.14$, $p = 0.94$, partial $\eta^2 = 0.00$.

Thus, the results do not support the third hypothesis: Completion of worked-out examples of explanation did not produce significantly more inclusion of the target principles during the writing tasks, compared to problem solving. Instead, both groups showed a significant linear increase in target principles across the first four writing activities (Table 4).

Table 4.

Mean Total Number of Target Principles Added for First Four Writing Tasks

Treatment	N	Time 1	Time 2	Time 3	Time 4
			M (SD)		
Completion	16	0.50 (0.52)	1.00 (0.89)	2.13 (1.31)	2.75 (1.57)
Problem-solving	32	0.41 (0.50)	0.78 (0.83)	1.81 (1.09)	2.54 (1.45)

The fourth hypothesis stated that completion of worked-out examples of explanations, compared to problem solving to write complete explanations, would produce lower cognitive load, as measured by Likert scale self-reported difficulty for each writing task. Mauchly's test indicated that the sphericity assumption was not violated, $p > 0.05$. The repeated measures ANOVA did not find significant between-group differences for reported difficulty, $F(1, 46) = 0.39$, $p = 0.53$, partial $\eta^2 = 0.01$. Also, the ANOVA did not significant within-group effects of time on the reported difficulty, $F(3, 138) = 0.30$, $p = 0.82$, partial $\eta^2 = 0.01$. Accordingly, there was neither a significant within-group linear trend found with the polynomial planned contrast, nor a significant growth of differences between the groups, $F(3, 138) = 0.97$, $p = 0.41$, partial $\eta^2 = 0.02$. Therefore, the fourth hypothesis was rejected: Completion of worked-out examples of explanations, compared to problem solving, does not produce significantly lower cognitive load as measured by Likert scale self-reported difficulty for each writing task (Table 5).

Table 5.

Mean Difficulty by Treatment Group for First Four Writing Tasks

Treatment	N	Time 1	Time 2	Time 3	Time 4
			M (SD)		
Completion	16	5.69 (1.49)	5.06 (1.69)	5.06 (1.73)	4.88 (2.47)
Problem solving	32	5.28 (1.69)	5.29 (2.01)	5.55 (2.06)	5.58 (1.92)

Note. 1 (min score) = very, very difficult; 9 (max score) = very, very easy

The fifth hypothesis stated that completion of worked-out examples of explanation, compared to problem solving to write complete explanations, would produce lower cognitive load, as measured by Likert scale self-reported effort for each writing activity. Mauchly's test confirmed that the sphericity assumption was not violated, $p > 0.05$. The repeated measures ANOVA found significant between-group differences for perceived effort, $F(1, 46) = 4.42$, $p = 0.04$, partial $\eta^2 = 0.09$. Specifically, the completion group reported significantly less perceived effort over the first four writing tasks, compared to the problem solving group (Table 6). The ANOVA did not find significant within-group effects of time on perceived effort, $F(3, 138) = 0.93$, $p = 0.43$, partial $\eta^2 = 0.02$. Likewise, there were neither significant within-group linear trends found with the planned polynomial contrast, nor a significant growth of differences between the groups, $F(3, 138) = 1.34$, $p = 0.26$, partial $\eta^2 = 0.03$. Therefore, the fifth hypothesis was accepted:

completion of worked-out examples of explanation, compared to problem solving to write complete explanations, produces lower cognitive load as measured by Likert scale self-reported perceived effort for each writing activity.

Table 6.

Mean Effort by Treatment Group and Time for First Four Writing Tasks

Treatment	N	Time 1	Time 2	Time 3	Time 4
			M (SD)		
Completion	16	5.69 (1.89)	5.81 (1.38)	6.50 (1.55)	5.94 (1.77)
Problem-solving	32	6.62 (1.88)	6.99 (1.74)	6.69 (2.32)	7.18 (1.47)

Note. 1(min score) = very, very little effort; 9 (max score) = very, very much effort

Table 7.

Summary of Results

Dependent Variable	Effect of Treatment?	Effect of Time	Time by Condition Interaction
Total Principles	**PS > C**	**Linear**	**More rapid gains for C**
Target Principles	NS	**Linear**	NS
Reported Difficulty	NS	NS	NS
Perceived Effort	**PS > C**	NS	NS
Principles in Sixth Writing Task	PS > C		
Evolution Post-test	**PS > C**		

Note. *NS* = non-significant results, *C* = completion group, *PS* = problem solving group, p<.05 are in boldface

Chapter 4

Discussion

General

Cognitive load theory has been used to inform instructional design in variety of learning contexts (Sweller et al., 2011). Evolutionary principles are difficult for many students to learn, and are often perceived as difficult (Alters & Nelson, 2002; Bishop & Anderson, 1990; Engel Clough & Wood-Robinson, 1985; Nieswandt & Bellomo, 2009). Previous studies examining writing-to-learn in evolution have asked students to write open-ended responses (Nehm et al., 2012; Nieswandt & Bellomo, 2009), or use learning progression lists based on specific concepts (Furtak et al., 2012). However, results from these studies indicate that when asked to explain evolutionary phenomena, students lack cognitive strategies for linking and transferring key evolutionary terms to written explanations (Nieswandt & Bellomo, 2009). Consequently, this study sought to investigate a cognitive strategy using a very structured method of instruction: teaching students to write evolutionary explanations using six Darwinian principles. The explanation, which includes relationships between the six principles, constituted a schema.

The study investigated two methods of instruction: The experimental group completed faded, worked-out examples of explanations; and the comparison group wrote full explanations, a procedure that is referred to in the cognitive load literature as using "problem solving." This expectation was based on empirical research concerning other learning activities. There is also some evidence that when solving full problems, novice learners rely on means-end problem solving, which imposes a high cognitive load (Sweller, 1988; Sweller et al., 2011).

Overall, both treatment groups demonstrated substantial learning gains, as measured by significant differences between evolution pre-test and post-test scores (Table 2). As they progressed from the first to fourth writing task, both groups also included an increasing number of total and target Darwinian principles. Therefore, students appeared to acquire schemas as they progressed through the lesson sequence and writing tasks. In addition, for the final writing task – the sixth writing activity – most students were able to construct explanations and apply most Darwinian principles to a novel scenario in a valid manner. Altogether, these results are favourable compared to many previous descriptive studies on secondary students' understanding of evolution (Alters & Nelson, 2002; Bishop & Anderson, 1990; Engel Clough & Wood-Robinson, 1985; Furtak et al., 2012; Nehm et al., 2012; Nieswandt & Bellomo, 2009). These gains and favourable results suggest that both completion and problem solving writing activities were effective.

Contrary to our hypotheses, participants in the problem solving group scored higher on several dependent variables: total principles for the first four writing tasks; scores for the sixth writing task; and scores for the evolution post-test. The exception was self-reported perceived effort for each writing task, for which the completion group, as hypothesized, showed significantly lower cognitive load. Three interpretations are proposed here as possible explanations for these results. It will be argued that the preferred interpretation is transfer complexity, and two alternative interpretations are the expertise reversal effect and time on task.

Interpretations

Preferred interpretation: transfer complexity. A possible explanation for the between-group differences for the sixth writing task scores, evolution post-test scores, and total number of Darwinian principles in writing activities concerns the effects of task characteristics on transfer. Previous research has demonstrated a transfer complexity hypothesis. Simple tasks support more rapid acquisition with fewer errors; however, more complex tasks, such as problem solving, require more effort and result in improved performance on transfer tasks (van Merriënboer & Sweller, 2005). In this study, writing full explanations using problem solving is complex because of the high number of elements interacting simultaneously. For the writing activities, the elements are Darwinian principles. To construct a satisfactory explanation, a student must consider how each of the principles fits together to produce the evolution of a given trait.

On the other hand, a worked-out example represents a less complex task. Indeed, for the first five tasks, completion students were required to include fewer principles, compared with the problem solving students. To put this differently, the completion condition actually required students to apply any given Darwinian principle, particularly those earlier in the explanatory sequence, to a smaller number of phenomena, and hence to a narrower range of phenomena. This may have prepared them less well for transfer. The transfer complexity hypothesis is supported by results from the study: The problem solving group reported significantly greater cognitive load as measured by self-reported perceived effort. Interestingly, there were no significant within-subject differences for the effect of time on perceived effort, suggesting that the act of writing explanations using problem solving required much effort and was a complex activity, regardless of whether it was the first or last writing task. Self-reported difficulty would be expected to be greater for the problem solving group if problem solving was a more complex task; however, there were no significant differences found for this measure between the two groups.

Alternative interpretation: expertise reversal effect. The significantly higher post-test scores, as well as the marginally higher sixth writing task scores achieved by the problem solving group may also be explained by the *expertise reversal effect*. The expertise reversal effect implies that students with higher knowledge benefit from higher cognitive load conditions, and that redundant information constitutes extraneous cognitive load (Kalyuga et al., 2001; Sweller et al., 2011). At the beginning of the learning process, students in both treatment groups could be considered to be at a relatively novice level, as determined by the pre-test (Table 1). As students progressed through the lesson sequence, they could be considered more expert: By the latter part of the study, most students were constructing explanations of evolution that included most Darwinian principles. At this point, all students were possibly ready to benefit from a more challenging condition requiring greater effort, such as writing complete explanations using problem solving. Conversely, according to cognitive load theory, the completion condition would be considered to impose extraneous cognitive load on a relatively expert student. The need to accommodate a partially worked example would conflict with the student's ability to derive a solution from her or his existing schema.

This interpretation is partially supported by the results: On average, students in both conditions rated the difficulty of the writing activities as moderate (Table 5). Consequently, they may have benefitted from the challenge of the problem solving condition more than the completion condition.

However, the expertise reversal effect also predicts that a less challenging task would impose a higher cognitive load. This was not the case: Completion students reported significantly less effort across the four writing tasks (Table 6), and there were no significant differences between treatment groups for reported difficulty (Table 5). Therefore, because completion students did not report higher cognitive load as operationalized by self-reported difficulty or self-reported perceived effort, the results do not fully support the expertise reversal effect interpretation.

Second alternative interpretation: time on task. These results can also be explained by time on task, which is another factor affecting cognitive load and learning efficiency. Specifically, increased time on task can cause a learner to perceive a task as more difficult, requiring greater cognitive load (Paas, Tuovinen, Tabbers, &Van Gerven, 2003). Although time on task was not measured in this study, students in the problem solving group were asked to write complete explanations involving all six steps of the explanation; students completing worked-out examples were required to write less than six steps. Therefore, students in the problem solving group probably spent more time on task.

This interpretation is supported by some results: Problem-solving students reported significantly more effort across the first four writing tasks, compared to students in the completion group (Table 6).

However, this interpretation is not fully supported, because there were no significant differences between the completion and problem solving groups for reported difficulty (Table 5). The increased time on task interpretation would predict that problem solving students would experience more difficulty during the writing tasks.

Educational Implications

Asking students to write explanations of evolution has benefits over time, and results in the increased conceptual understanding of evolutionary theory. Furthermore, writing complete explanations using all six principles is more effective than completing faded, worked-out examples. Therefore, educators should encourage students to write complete explanations of evolutionary phenomena to increase schema acquisition and transfer of evolutionary concepts.

Limitations

Cluster sampling conveniently reduced the time needed to obtain participants; this also facilitated greater ease in securing consent from administrators and parents, because entire classrooms were left intact. Although cluster sampling allowed whole classrooms to benefit from the writing treatments, rather than a few students in each class, the quasi-experiments introduced two confounding variables: class and teacher. Consequently, these confounding variables (class and teacher) cannot be eliminated as alternative explanations of this study's results.

Another limitation was the negative inter-item reliability of pre-test Form A. However, this statistic suggests a theoretically interesting pattern. Items that performed well statistically on the pre-test were generally prediction items that required students to anticipate that adaptive traits would become prevalent in the environment. Conversely, the problematic test items required students to select explanations of why (through what principles), these traits would become prevalent. These items apparently were valid, because they were based on previous research on students' understanding of evolution. The negative inter-item reliability and negative correlation of these items with the total indicates that students who scored relatively high on the test as a whole tended to score low (below chance) on these items. At the same time, on average, pre-test scores were low. This set of patterns suggests the following: At pre-test, more knowledgeable students were able to predict evolutionary changes, resulting in a relatively high total test score; however, they applied misconceptions to explanations, thus scoring below chance on the problematic items. Conversely, less knowledgeable students were unable to predict evolutionary phenomena at a level above chance, resulting in a low total score; conversely, they appeared to guess on explanation questions, resulting in a score at a chance level. At post-test, most students had resolved their misconceptions, and so scored above chance on both prediction and explanation items. This resulted in positive inter-item reliability.

In addition, for the total number of principles, it should be noted that the problem solving group scored higher across writing activities due to inherent differences in the task. Students in the problem solving condition received points by including any Darwinian principle that they could generate. On the other hand, students in the completion condition could only add principles that were not already in the worked part of the explanation, giving them less opportunity to score points. Also, for the initial writing activities, students in the completion condition had the opportunity to add very few principles (e.g., one, two), and on later writing activities, they had the opportunity to add more (e.g., four, five), so this inherently led to a greater rate of increase in principles for the completion group.

Missing data was an issue in this study, which may have distorted inferences about the participant population. Indeed, some non-significant results could have resulted from reduced statistical power caused by the small sample size, especially in the completion class. In addition, four students did not complete the post-test and were removed from the study. Six writing tasks in total were given to all students; however, several students were missing one or two of the writing tasks. Therefore, scores for the first four writing tasks written by every participant were used. For example, for one participant, this may mean the first, second, fourth and fifth writing task were used; for another participant, the first, third, fourth and fifth writing tasks were used. Finally, some regression imputed values were used. This method generated the most probable values; however, regression imputation tends to reduce variance in data. This limitation was tempered by the fact that the imputed values constituted less than one percent of all data values; they were applied mainly to effort and difficulty scores, and no evolution post-test scores were imputed.

There was an experiment-wise increase in the probability of a false rejection of the null hypothesis, because of the use of multiple dependent variables. If the number of participants were larger, multivariate analysis could be used to control this risk; however, the number of participants in this study was modest. This limitation is tempered by the fact that several dependent variables were statistically significant, and it is unlikely that all of these significant effects occurred by chance.

Future Research

For future research, replication of the study with more classes and more participants would be desirable in order to increase statistical power. For example, increased participants may provide a better estimate of the effects of completion and problem solving on self-reported difficulty for each writing task, a measure that was found to be insignificant. This in turn may help us to test for an expertise reversal effect, and provide more accurate measures of cognitive load in general. In addition, in order to control for time on task, the completion group could be asked to complete two worked-out examples for some sessions. The effectiveness of completing worked-out examples, compared to problem solving, could also be tested for other writing-to-learn activities in science.

In this study, both groups received similar supports to constitute feedback: Both groups received two worked problems in the focus lesson, visual posters of the six Darwinian principles, and written comments about each of their six writing tasks. These feedback elements were consistent between the two groups in terms of structure and timing. In future research, this feedback could be more varied, and tailored specifically to the participants' expertise levels

In addition, more rapid diagnostic assessments could be used to quickly assess learning expertise levels (Blayney, Kalyuga, & Sweller, 2010). For example, if formative assessments showed increased levels of expertise, worked-examples could be faded more quickly; if assessments measured novice levels of expertise, worked-examples could be faded in a more gradual manner. Likewise, more research is needed to investigate mediating mechanisms, such as feedback, to determine the effects of far-transfer for both forward and backward fading (Renkl et al., 2002).

Conclusion

This study investigated the effects of two treatments (completing worked-out examples or problem solving) on six measures: a final writing task assessment (measuring transfer of concepts to a novel scenario); an evolution post-test; number of total and target Darwinian principles included; reported difficulty; and perceived effort. Both groups used the cognitive structure of the six Darwinian principles. Both completion and problem solving groups demonstrated significant learning gains as measured by scores of the pre- and post-test; both groups also demonstrated learning gains as measured by the number of principles added over the first four writing tasks. However, students in the problem solving condition scored significantly higher in the evolution post-test, and scored marginally higher in the sixth and final writing task, than students completing worked-out examples. The problem solving group also included significantly more total Darwinian principles in the first four writing tasks. These results suggest that problem solving is more efficient for schema acquisition and concept transfer, compared with completing worked-out examples. These results can be explained by transfer complexity, expertise reversal, and time on task interpretations. Overall, these findings confirm cognitive load as a promising tool for informing future writing-to-learn structures.

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Appendix A. Test Form A (pre-test or post-test)

1. Explain how living things change over generations.

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2. **The deer mouse of Nebraska is normally dark brown in colour and lives in the woods. However, a subset of this population moves into a sandy area called Sand Hills. What do you predict will happen to this population subset? Please circle the correct answer.**

(a) Future generations of this population will remain a dark brown colour.
(b) Future generations of this population will become lighter, more sand-like, in colour.
(c) Future generations of this population will consist of individuals that are dark brown in colour, as well as individuals that are a lighter, sand-like, in colour.

This will happen because …

(a) The ancestral population of the deer mouse contains individuals that can morph from darker to lighter colours.
(b) The ancestral population of the deer mouse had individuals that varied from darker to lighter colours.
(c) The move to Sand Hills caused individuals to need to change colour to hide in their surroundings.

3. **Pesticides are often used to kill insects. After a pesticide is applied, which of the following scenarios is likely to occur?**

(a) Pesticides always maintain their effectiveness in killing insect populations.
(b) Pesticides will be effective at first, but then may lose their effectiveness over a few generations.
(c) Pesticides will never be effective in killing the insect population.

This will happen because …

(a) Insects with pesticide-resistance exist in the population, and increase in frequency.
(b) Some insects respond to pesticides by developing pesticide-resistance.
(c) The pesticide causes mutations for pesticide-resistance to occur.

4. **On the Galapagos Islands, there are populations of finches that are similar except for the shapes and sizes of their beaks, which vary by island. On island A, the main food source is large, hard seeds. Which variation of beak is most likely to be prevalent for finches on island A?**

(a) Large, sharp, and tough beaks
(b) Flat, smooth, wide beaks
(c) Smaller, narrower beaks

How did finches on island A evolve these beaks?

(a) Individual finches morphed their beak shape into ones that would be appropriate for the food source, allowing them to survive and reproduce.
(b) In the older population, finches with appropriately-shaped beaks were able eat more large, hard seeds than birds with inappropriately-shaped beaks.
(c) All finches with beaks appropriate for eating large, hard seeds flew from other islands to live on island A.

5. **Biologists think that ancestors of polar bears had dark fur. Why do polar bears today have white fur?**

(a) White fur became more prevalent by random chance.
(b) White fur provides more warmth than dark fur.
(c) White fur allows for easier camouflage in the snow.

Explain how bears with white fur accumulated in the population.

(a) Bears with lighter fur were able to camouflage more easily in the environment, allowing them to survive and reproduce at greater rates than darker furred bears.
(b) Bears with lighter fur have stronger genes than bears with darker fur.
(c) Darker polar bears developed white fur to camouflage with the environment, allowing them to hunt prey more easily. These bears survived and reproduced.

6. **The American rat snake can be found in a variety of different colours, depending on its geographical location. What colour of rat snake would you expect to live in a forest habitat?**

(a) The rat snake would be orange.
(b) The rat snake would be green.
(c) The rat snake would be yellow, with black stripes.

How would this colour evolve?

(a) When rat snakes are born, their surroundings cause their skin colour to change to one that will help the individual blend more easily with its surroundings.
(b) The snakes with coloured skin that best blended with its surroundings were more likely to survive.
(c) Each individual rat snake's skin colour will depend on the food sources that are available in the area.

7. The ancestor of the modern whale was a mammal that lived entirely on land. Three students give explanations for why the whale now lives entirely in the ocean. Whose explanation do you agree with?

(a) Daria: "One day, there was a shortage of food on land. The entire population of the ancestral mammal moved into the ocean in order to survive."
(b) Sarah: "There was more food in the water. Some ancestral mammals developed the ability to live in the ocean, and were able to access these food sources."
(c) Mark: "Since there were more food sources in the ocean, individuals who could remain in the ocean were better able to access these food sources."

How did the ability to live in the ocean evolve in the population?

(a) Gradually. Some individuals could live in the ocean and these numbers increased.
(b) Suddenly. The entire population moved into the ocean at the same time.
(c) Quickly. Once one individual whale learned to live in the ocean, the ability to do so spread quickly through the population.

8. **A team of Japanese scientists finds a single, novel species of bacteria in wastewater ponds behind a nylon factory. Which of the following is probably true for these bacteria?**

(a) Most of these bacteria are killed off by nylon particles.
(b) These bacteria primarily feed on the nylon particles.
(c) These bacteria primarily feed on particles other than nylon.

How did these bacteria evolve?

(a) Previous generation of the bacteria did not eat nylon, but when they were surrounded by the wastewater they learned to eat nylon.
(b) Previous generations of the bacteria were not able to eat nylon, so when they moved into these wastewater ponds and tried to eat nylon, they died.
(c) Previous generations included a small population that could eat nylon. In this environment, those who ate nylon were more likely to survive and reproduce.

Appendix B. Test Form B (pre-test or post-test)

1. How do organisms evolve?

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2. **When certain bacteria are treated with an antibiotic, which of the following is likely to occur? Please circle the best answer.**

(a) The bacteria population will be unaffected and survive.
(b) The bacteria population will die from the antibiotic.
(c) Some bacteria will survive the antibiotic, and other bacteria will die.

This will happen because …

(a) The antibiotic causes mutations for resistance to occur.
(b) Bacteria with resistance are already present in the population and increase in frequency.
(c) Bacteria respond to their hostile environment by developing resistance.

3. **In the Lacandon rainforest jungle in Guatemala, trees can grow to an average height of 30 meters. How will the heights of these trees change in future generations of the rainforest?**

(a) The trees will get taller.
(b) The trees will get shorter.
(c) There will be no change to the height of the trees.

Three students give explanations for the above phenomenon. Whose explanation do you agree with?

(a) Michael says: "In the rainforest, there are more nutrients and the climate is hot throughout the year."
(b) Janelle says: "Trees are able to grow year round in the rainforest."
(c) Raquel says: "In the rainforest, trees that are taller are able to receive more sunlight than trees that are shorter."

4. **The male ancestors of the peacock did not have the bright, colourful feathers that they have today. Which of the following must have occurred during evolution?**

(a) Some male peacocks with duller feathers developed the ability to grow colourful feathers.

(b) Male peacocks with colourful feathers increased in frequency in future generations.

(c) Male peacocks ate new foods that mutated their genes, allowing them to grow colourful feathers.

This occurred because …

(a) Females peacocks prefer mating with males with more colourful feathers, because they are more impressive.

(b) Females find male peacocks with colourful feathers are more pleasant to look at.

(c) Female peacocks prefer mating with males with more colourful feathers, because colourful feathers blend more easily into their surroundings.

5. **Each colony of African warrior ants can produce chemical signals that let others know that they are in the same compound. However, some warrior ants can imitate the chemical signals of other colonies. How did this ability arise?**

(a) Warrior ants learn the chemical signals of enemy colonies and their glands learn to produce similar signals.

(b) Some warrior ants carried a mutated gene that allowed them to imitate the chemical signals of another colony.

(c) Some warrior ants were exposed to chemical signals of another colony, which were absorbed and reproduced.

Three students made the following predictions. Whose prediction do you agree with?

(a) Sandy: “The imitating ants will give fellow ants in their colony the ability to create similar chemical signals, thus increasing the total number of imitating ants. These imitating ants will be able to penetrate other colonies and take over their resources, increasing their probability of surviving and reproducing.”

(b) Sayed: “The ants that can imitate chemical signals will penetrate and attach other colonies and take over their resources, increasing their probability of surviving and reproducing over those ants that are unable to imitate chemical signals.”

(c) Marci: “The ants that can imitate chemical signals will eventually integrate with other colonies and use food and habitat resources in a cooperative manner.”

6. **Bipedalism is the ability for an organism to move around by using its two rear legs. Human ancestors evolved bipedalism (walking upright). Which of the following statements is probably true for the ancestral population?**

(a) The ancestral population was uniform, no ancestors could walk upright.
(b) Some ancestors could walk upright, others could not.
(c) The entire ancestral population has always been able to walk upright.

Explain the advantages of bipedalism for humans.

(a) Individuals that could walk upright had a more elevated eye position, allowing them to see greater distances and avoid predators.
(b) Female individuals that could walk upright could carry heavier loads when pregnant, allowing for more successful reproduction rates.
(c) Both (a) and (b) could be correct.

7. **Lizards have been used to study natural selection. In a study, scientists remove the predators of the lizard, but keep them in their natural environment. As a result, future generations of lizards …**

(a) Will have a higher frequency of smaller sized individuals.
(b) Will have a higher frequency of larger sized individuals.
(c) Will consist of smaller individuals that will grow larger during their lifetime.

Explain how this size change will accumulate in the population.

(a) The whole population will be able to grow larger when predators are removed.
(b) Some lizards are larger than others, and their numbers will increase.
(c) Some lizards are smaller than others, and their numbers will increase.

8. **Seals remain underwater without breathing for nearly 45 minutes as they hunt for fish, but their ancestors could stay underwater for only a couple of minutes. How has this trait evolved?**

(a) The ancestors trained themselves to stay underwater without breathing for longer and longer periods of time.
(b) An individual seal discovered that by staying underwater, she could catch more fish. She then gave birth to offspring that could also remain underwater for longer times.
(c) Some seals could hold their breath underwater longer than other seals. Seals that could stay underwater for longer periods of time, increased in frequency.

Why is staying underwater for longer periods an advantageous trait?

(a) The seals can catch more fish and survive.
(b) The seals can hide more easily from predators.
(c) Both (a) and (b) could be correct.

Appendix C. Introductory focal lesson – two fully-worked examples

Example 1

Article source: *Early bats flew first, developed "sonar" later* (National Geographic, 2008).

Focus Question: Explain, using the six Darwinian principles, how bats evolved internal sonar (echolocation) to navigate and detect prey.

1. Random mutations resulting from sexual reproduction resulted in a variety of bats in the ancestral population. *(Source of variability)*
2. Some bats had the ability to create high pitched-sounds, and therefore could better avoid obstacles and detect prey by listening to the sounds bounce back. Other bats did not have this ability. *(Intra-species variability)*
3. Those bats that had the ability to create high pitched-sounds were more likely to survive than bats that couldn't create high-pitched sounds. That is, they could fly without encountering obstacles, and were more easily able to find food sources and survive. *(Differential survival rates)*
4. Therefore, bats that could create high-pitched sounds probably reproduced more than those bats that couldn't create these sounds. *(Reproductive advantage)*
5. These bats reproduced and passed on more of their genes to their offspring, increasing the likelihood that their offspring also inherited the ability to create high-pitched sounds. *(Accumulation of change)*
6. As such, the proportion of bats that could create these high-pitched sounds increased within the population, and echolocation became prevalent within the population. *(Changes within a population)*

Example 2

Article source: *In crocodile evolution, the bite came before the body* (National Geographic, 2004).

Focus Question: Explain, using the six Darwinian principles, how today's semi-aquatic crocodiles evolved from their entirely land-living ancestor, *Junggarsuchus sloani.*

1. Random mutations resulting from sexual reproduction resulted in a variety of crocodiles in the ancestral population, which primarily lived on land. *(Source of variability)*
2. Some crocodiles had the ability to live in the water, and had bodies more suited to swimming, than other crocodiles in the population. *(Intra-species variability)*
3. These crocodiles could hunt in the water while being submerged, and hidden, from their prey. Therefore, they were more likely to successfully hunt prey and survive than crocodiles that could not enter the water. *(Differential survival rates)*
4. Therefore, the crocodiles that could live in the water were more likely to reproduce than those crocodiles that lived on land. *(Reproductive advantage)*
5. These crocodiles reproduced and passed on more of their genes to their offspring, increasing the likelihood that their offspring also inherited the ability to live in the water. *(Accumulation of change)*
6. As such, the proportion of crocodiles that could live and hunt in the water increased within the population, and became more prevalent within the ancestral population. *(Changes within a population)*

Appendix D. Teachers' checklist for evolution lesson/ writing task sequences

Focal Lesson

- ☐ Post the six Darwinian principles at the front of the classroom. This poster must remain at the front of the class during the entire unit.

- ☐ Introduce the six Darwinian principles *(source of variability, intraspecies variability, differential survival rates, reproductive advantage, accumulation of change,* and *changes within a population),* and describe why these principles help to explain the process of evolution.

- ☐ Give students two fully-worked examples of evolutionary explanations, and have them identify which "step" (i.e. Darwinian principle) corresponds to each part of the sample explanation (Appendix C).

- ☐ Engage students in a reflection activity – have students write two compositions paraphrasing the concepts in each worked example. Have students share their ideas in a think-pair-share.

Day 1 – Lesson on early ideas about evolution (text pp. 187-189)

- ☐ Present lecture and have student write notes about the following concepts: evidence for evolution, the age of the earth, and the ideas of Lyell, Malthus and Lamarck.

- ☐ Have students complete the following textbook questions on page 194 of *Pearson Biology Source 11*: #1-7, 10.

- ☐ Have students complete the a vocabulary activity, including the following terms: *evolution, natural selection, analogous structures, adaptive radiation, uniformitarianism, fitness, gene pool, convergent evolution, adaptation, survival of the fittest, microevolution, descent with modification, homologous structures, sexual selection, gradualism, variation, vestigial structures, genetic drift, speciation, punctuated equilibrium*

Day 2 – First writing task and first questionnaire

- ☐ Give students the first writing task (experimental condition: worked example with one step removed) and the accompanying PDF article. Students have 20 minutes to complete the writing task.

- ☐ Give students the first Likert scale questionnaire.

- ☐ Give students time to complete work from, or take up work from, Day 1.

Day 3 – Lesson on Darwin's observations and theory development (text pp. 189-194)

- ☐ Give students written feedback on the first writing task. Include 1-2 comments, in addition to the checklist.
- ☐ Present lecture and have student write notes about the following concepts: Darwin's voyages, principle observations of species characteristics, and theory development.
- ☐ Have students complete the following textbook questions on page 194 of *Pearson Biology Source 11*: #12-14.
- ☐ Have students watch the video, *Origin of Species: Beyond Genesis.*

Day 4 – Second writing task

- ☐ Give students the second writing task (experimental condition: worked example with two steps removed) and the accompanying PDF article. Students have 20 minutes to complete the writing task.
- ☐ Give students the second Likert scale questionnaire.
- ☐ Give students time to complete work from, or take up work from, Day 3.

Day 5 – Lesson on Darwin's model of natural selection (text pp. 195-199)

- ☐ Give students written feedback on the second writing task. Include 1-2 comments, in addition to the checklist.
- ☐ Present lecture and have student write notes about the following concepts: descent with modification, the struggle for existence, variation, the role of the environment, and the theory of natural selection.
- ☐ Have students complete the following textbook questions on page 199 of *Pearson Biology Source 11*: #1-3, as well as on page 209: #1-4.
- ☐ Have students watch the video, *Charles Darwin and the Tree of Life.*

Day 6 – Third writing task and second questionnaire

- ☐ Give students the third writing task (experimental condition: worked example with three steps removed) and the accompanying PDF article. Students have 20 minutes to complete the writing task.
- ☐ Give students the third Likert scale questionnaire.
- ☐ Give students time to complete work from, or take up work from, Day 5.

Day 7 – Lesson on evidence for evolution (text pp. 199-204)

- ☐ Give students written feedback on the third writing task. Include 1-2 comments, in addition to the checklist.
- ☐ Present lecture and have student write notes about the following concepts: the fossil record, geographic distribution, homologous structures, vestigial structures, analogous structures, comparative development, and molecular biology.
- ☐ Have students complete the following textbook questions on page 209 of *Pearson Biology Source 11*:: #5-14.
- ☐ Have students complete the Active Folder, on *Adaptations.*

Day 8 – Fourth writing task

- ☐ Give students the fourth writing task (experimental condition: worked example with four steps removed) and the accompanying PDF article. Students have 20 minutes to complete the writing task.
- ☐ Give students the first Likert scale questionnaire.
- ☐ Give students time to complete work from, or take up work from, Day 7.

Day 9 – Lesson on artificial selection and relationship to natural selection (text pp. 205-208)

- ☐ Give students written feedback on the fourth writing task. Include 1-2 comments, in addition to the checklist.
- ☐ Present lecture and have student write notes about the following concepts: artificial selection (and how it serves as evidence for Darwin's theory of natural selection), changes in finch beak shape, and antibiotic resistance in bacteria.
- ☐ Have students complete the following textbook questions on page 210 of *Pearson Biology Source 11*: #8-9.
- ☐ Have students complete online simulation Gizmo about evolution, called *Evolution: Natural and Artificial Selection,* including the Student Exploration Sheets.

Day 10 – Fifth writing task and third questionnaire

- ☐ Give students the fifth writing task (experimental condition: worked example with five steps removed) and the accompanying PDF article. Students have 20 minutes to complete the writing task.
- ☐ Give students the fifth Likert scale questionnaire.
- ☐ Give students time to complete work from, or take up work from, Day 9.

Day 11 – Lesson on genetic variation and sexual selection (text pp. 212-221)

- ☐ Give students written feedback on the fifth writing task. Include 1-2 comments, in addition to the checklist.
- ☐ Present lecture and have student write notes about the following concepts: variation in gene pools, roles of mutation and sexual recombination, microevolution, genetic drift, bottleneck effect, Hardy-Weinberg equilibrium, founder effect, and gene flow.
- ☐ Have students complete the following textbook questions on page 223 of *Pearson Biology Source 11*: #1-14.
- ☐ Have students complete online simulation Gizmo about evolution, called *Evolution: Mutation and Selection ,* including the Student Exploration Sheets.

Day 12 – Sixth writing task

- ☐ Give students the sixth writing task (experimental condition: all steps removed) and the accompanying PDF article. Students have 20 minutes to complete the writing task. This writing task will serve as one of the post-tests.
- ☐ Give students the sixth Likert scale questionnaire.
- ☐ Give students time to complete work from, or take up work from, Day 11.

Day 13 – Inquiry activity

- ☐ Give students the inquiry activity on industrial melanism and the peppered moth. Students should be randomly put into groups. Have students analyze and graph results, and hand in conclusion statements.

Appendix E. Checklist evaluating explanations of evolution & poster to be displayed at the front of both control and experimental classrooms

Checklist is adapted from Asterhan and Schwarz (2007, p. 64).

Completed ✓	**Sub-explanations – Darwinian principles**
	discussed *source of variability*
	discussed *intra-species variability*
	discussed *differential survival rates*
	discussed *reproductive advantage*
	discussed *accumulation of change*
	discussed *changes within a population*

Appendix F. Six completion writing tasks

Students in the experimental condition will receive the worked examples as outlined below.

The comparison condition will not receive worked examples: this class will be given a blank, numbered response sheet and will be given the task to “explain the evolutionary process behind the phenomena you have read about, using Darwinian principles.” Control students will receive the focus question and additional task as described in the examples on the following pages.

Completion Task #1 (one step removed) – COMPLETE THE LAST STEP!
Topic: Snakehead fish found in British Columbia (June 2012), CBC News

Task: *Complete the* *last step* *of the evolutionary explanation, using Darwinian principles.*
Focus question: *Explain how the snakehead fish evolved to live on land.*

1. The ancestors of the snakehead fish lived only in the water. Random mutations led to some individuals developing lung-like structures.

2. Within the ancestral species, there were individuals with varying degrees of lung-like structures; some had no lungs, and some had full lungs.

3. The individuals with lungs were able to live outside of the water, on land, for an extended period of time, unlike the individuals without lung structures. As such, ancestors with lungs were more likely to survive, because they could benefit from the food and shelter found on land (for example, hunting frogs or even small mammals).

4. The increase in food resources allowed more of the individuals with lungs to reproduce more offspring relative to those without lungs.

5. As such, more genes for the lung structures were passed on to offspring, leading to a greater proportion of these genes accumulating in the ancestral population.

6.

Additional task: Please label each part of the explanation with the **Darwinian principle** that corresponds to it.

Completion Task #2 (two steps removed)
Topic: Pygmy elephant found on Flores (October 2004), National Geographic

Task: *Complete the <u>last two steps</u> of the evolutionary explanation, using Darwinian principles.*
Focus question: *Explain how the pygmy elephant evolved to be its smaller size.*

1. The ancestors of the pygmy elephant (a subset of Asian elephant) reproduced sexually, producing genetic mutations while doing so, leading to a variety of offspring.

2. The ancestral population varied in height and, some were more round and had longer tails.

3. As it states in the article, a small population was shipped to the sultan of Borneo. This population probably had a greater proportion of individual elephants that were shorter, rounder, and had longer tails. Because they were a gift to the sultan, this population was protected and survived.

4. On the island of Borneo, these elephants only sexually reproduced with individuals within the same population to produce viable offspring. Because they were not competing with taller mates from the ancestral population, this smaller Borneo population was reproductively successful.

5.

6.

Additional task: Please label each part of the explanation with the **Darwinian principle** that corresponds to it.

Completion Task #3 (three steps removed)
Topic: Halibut eye migration, Halibut Biology

Task: *Complete the* *<u>last three steps</u>* *of the evolutionary explanation, using Darwinian principles.*
Focus question: *Explain how the halibut evolved to have eyes on its backside (dorsal side).*

1. The ancestors of the halibut used to swim upright, and would reproduce sexually to create offspring with a variety of genetic mutations and physical characteristics.

2. The locations of the eyes of the offspring would vary from individual to individual. Within the species, there were some individuals with eyes located closer to the dorsal side (backside) of the fish.

3. These individuals were able to see when they lay down flat on the bottom of the ocean. Because they could lay flat on the bottom, these individuals could camouflage themselves effectively from predators and therefore survived at a greater rate than those individuals who had eyes on the sides of the head (and could not lie flat on the ocean floor).

4.

5.

6.

Additional task: Please label each part of the explanation with the **Darwinian principle** that corresponds to it.

Completion Task #4 (four steps removed)
Topic: Bacteria resistant to antibiotics (April 2012), Globe and Mail

Task: *Complete the <u>last four steps</u> of the evolutionary explanation, using Darwinian principles.*
Focus question: *Explain how the super-bacteria evolved to have its antibiotic resistance.*

1. Bacteria can reproduce sexually or asexually very quickly, and when they do, there are random mutations.

2. Ancestral generations of the bacteria found in New Mexico had individuals that varied: some could produce their own antibiotics, and others could not.

3.

4.

5.

6.

Additional task: Please label each part of the explanation with the **Darwinian principle** that corresponds to it.

Completion Task #5 (five steps removed)
Topic: Homo floreseinsis ("The Hobbit"), talkorigins.org

Task: *Complete the last five steps of the evolutionary explanation, using Darwinian principles.*
Focus question: *Explain how the homo floreseinsis evolved to its dwarf size.*

1. Ancestors of humans and homo floreseinsis reproduced sexually, creating offspring with varied characteristics.

2.

3.

4.

5.

6.

Additional task: Please label each part of the explanation with the **Darwinian principle** that corresponds to it.

Completion Task #6 (six steps removed) **Topic:** Mussels evolve quickly to defend against invading crabs, Science Daily

Task: *Complete <u>all six steps</u> of the evolutionary explanation, using Darwinian principles.*
Focus question: *Explain how the mussels evolved to have thicker shells.*

1.

2.

3.

4.

5.

6.

Additional task: Please label each part of the explanation with the **Darwinian principle** that corresponds to it.

Appendix G. Writing task – accompanying newspaper or magazine articles

Please see attached PDF files for the two articles for the focal lesson, as well as the six articles for the six completion tasks.

Appendix H. Post-task questionnaire (Likert scales)

Question 1. Please rate the *difficulty* of the written completion tasks, by circling the appropriate number.

Very, very difficult	1	2	3	4	5	6	7	8	9 Very, very easy

Question 2. Please rate the effort with which you completed the written tasks, by circling the appropriate number.

Very, very little effort	1	2	3	4	5	6	7	8	9 Very, very much effort

Curriculum Vitae

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