What Types of Feedback Enhance the Effectiveness of Self-explanation in a Simulation-Based Learning Environment?

by

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Abstract

In this research, self-explanation was prompted and feedback was supplied to help learners activate prior knowledge, detect misconceptions, and replace unscientific mental models with correct scientific models. The research investigated the effects of two types of tutor feedback on learning and conceptual change in a simulation inquiry environment: Elaborative feedback incorporated tutor explanation and knowledge of results feedback provided only confirmation or disconfirmation of learners' statements. Sixty-eight undergraduate students, with low prior knowledge in the physics of waves, were randomly assigned to receive either (a) self-explanation prompts with no feedback (NF), (b) self-explanation prompts with knowledge of results feedback (KRF), and (c) self-explanation prompts with elaborative feedback (EF). A pretest-posttest design was used to investigate participants' knowledge gain and conceptual change resulting from learning tasks they performed by interacting with a physics simulation and explaining what they observed. The simulation, learning tasks, and knowledge tests focused on five fundamental principles of wave physics, four of which are often subject to misconceptions. Chi-square tests of association followed by pairwise Fisher's exact test comparisons revealed elaborative feedback was advantageous, but only for two of the four concepts prone to persistent misconception – the mechanism of sound propagation and the medium-speed relationship. The findings suggest that prompting learners to self-explain can be sufficient for learning, but only for concepts whose acquisition is not hindered by persistent misconceptions. For concepts prone to such misconceptions, elaborative feedback may be necessary for understanding phenomena at deep structural levels. It is proposed that self-explanation combined with elaborative feedback may be a highly effective instructional strategy across many scientific domains, especially in the context of simulation-based inquiry learning.

Keywords: feedback; self-explanation; misconception; learning; simulation

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Chapter 1.

General Overview and Purpose of Study

1.1. Introduction

Learning is an ongoing process by which we integrate new information into our existing repertoire of knowledge. We begin constructing knowledge at a very young age and continuously use our previously constructed knowledge to make sense of newly encountered information about our environment. In this process, we strive to make judgments about the world efficiently, which means we actively create meaning through structured and coherent reasoning to avoid the cost of storing and recalling specific details of past experiences (Richter et al., 2019). We generalize our experiences in the form of cognitive frameworks or abstract mental structures which can help us organize and interpret information (Piaget, 1977). Constructed schemas then enable us to predict the outcomes of many events (Ghosh & Gilboa, 2014) even if those events are not directly experienced by us.

The functionality of schemas, however, strongly depends on how well they can explain or be adapted to explain new conditions or phenomena (Anderson et al., 1978; Richter et al., 2019). If existing schemas cannot be upgraded to meet the new conditions of the environment, the process of knowledge acquisition may be blocked due to the contradiction, confusion, and faulty understanding that the learner encounters (Hewson & Hewson, 1984).

This conceptual conflict may be a fundamental reason for failure to learn scientific concepts (Hewson & Hewson, 1984; Trumper, 1997). There is much evidence that students continue to hold ideas that are inconsistent with established scientific concepts presented to them via school curricula (Bekkink et al., 2016; Potvin et al., 2014). These persistent incorrect or partially correct ideas sometimes appear to be highly coherent, logically linked, and more practical for understanding and making sense of the world (Chen et al., 2020; Fisher, 1985). For example, the idea that heavier objects would always fall faster than lighter ones and hit the ground first is an intuitively acceptable mental image that seems logical and observable. Deleting this model and replacing it with a new one that has more complications and conditions, such as the effects of absence or presence of air resistance on acceleration rate, can be a difficult process (Potvin et al., 2020).

Eliciting students' prior knowledge and their existing models of thinking is a critical step in the learning process (Braasch & Goldman, 2010; Marek et al., 1994). It allows students to encounter the discrepancy between their own cognitive structures and the external information and diagnose their erroneous models of thinking, which can ultimately lead to reconstructing schema in preparation for further learning. However, important challenges for educators are how to effectively obtain information about learners' existing knowledge, how to make misconceptions visible, and how to facilitate accurate formation of scientific concepts.

One of the most effective instructional strategies supporting learners' deliberate retrieval and examination of information from memory is self-explanation. Self-explanation, as a generative activity, facilitates recall of the specific knowledge required to handle a unique situation. Research shows that self-explanation promotes activation and elicitation of prior knowledge and leads to generation of inferences (e.g., Chi, 2000; Rittle-Johnson & Loehr, 2017; Roy & Chi, 2005) about conceptual relations and causal associations (Bisra et al., 2018; Chamberland & Mamede, 2015). According to self-explanation theory, the process of explaining a phenomenon within an appropriate context promotes learning through several mechanisms such as filling knowledge gaps and revising existing mental models through detecting errors and revealing paradoxes as well as resolving cognitive conflict (Chi et al., 1989; Chi et al., 1994; DeLeeuw & Chi, 2003; Ionas et al., 2012; VanLehn et al., 1992). Therefore, self-explanation prompts can act as retrieval tools facilitating activation of prior knowledge. Self-explanation prompts can be presented to elicit various types of knowledge such as prediction, reasoning, and meta-cognitive thinking. For example, justification prompts (Conati & VanLehn, 2001) elicit reasoning such as "This choice is correct because A and B have a causal relation," meta-cognitive prompts (Chi, et al., 1994) facilitate thinking about explanations through questions such as "How is the new knowledge related to what the learner already knows and why," and prediction prompts (Yeh et al., 2010) activate learners' existing knowledge by prompting them to predict and explain the upcoming behaviour of graphs, animations, or observed phenomena.

Although self-explanation is considered a powerful learning strategy for resolving cognitive conflict (Chi, 2000), it may hinder learning if student prior knowledge is inaccurate, insufficient, or inappropriate (Little-Johnson & Loehr, 2017). In this case, explaining one's ideas may hinder learning and bolster misconceptions as most novice learners have systematic preference for ideas that are more coherent and intuitive to them (Hewson & Hewson, 1984). The preference for explanations built on prior knowledge has been observed in learners at various levels, including young children (Bonawitz & Lombrozo, 2012).

As Rittle-Johnson and Loehr (2017) argue, "self-explanation is often more effective when learners are explaining content that they know is correct or incorrect rather than their own ideas" (p. 1505). Therefore, external tutor feedback may be necessary to identify and remediate learner's existing mental models.

In such cases, conceptual change instruction is crucial in revising learners' intuitive misconceptions (Posner et al., 1982). While this instruction can be provided in diverse ways, the present study investigates the effect of tutor feedback on learner explanations as a strategy for promoting conceptual change. Feedback is the information given by an agent/tutor/instructor about the learner's performance or understanding (Hattie & Timperley, 2007). This information can repair, revise, and remediate when a knowledge gap is present, or a misconception persists.

As Posner et al. (1982) argue, the first step in resolving misconceptions is experiencing dissatisfaction arising from cognitive conflict and failure to understand the new material. Therefore, if a learner's explanation is followed by feedback intervention, any persistent misconceptions or incomplete knowledge indicated by the explanation can be confronted, analyzed, understood, and corrected.

Feedback can also effectively reduce the cognitive load of learners, particularly novices or struggling students (e.g., Paas et al., 2003). Feedback can provide information that may be useful for correcting erroneous models of thinking, false assumptions, and misconceptions (e.g., Mory, 2004; Qian & Lehman, 2019).

In this research, self-explanation and feedback were introduced as integrative instructional strategies to promote activating prior knowledge, detecting misconceptions, and replacing flawed mental models with correct scientific models. These two strategies synergistically connect the three processes of activation, retrieval, and encoding information and facilitate requisite cognitive processes such as remembering, understanding, applying, analyzing, evaluating, and creating (Krathwohl, 2002).

The results of the present study provided evidence that self-explanation elicited knowledge and understanding; and feedback promoted knowledge organization, integration, and transfer (Butler et al., 2013). They suggest self-explanation may not be sufficient as a constructive activity if learners have incomplete, incorrect, and inappropriate knowledge about a particular topic. The results also showed that elaborative feedback plays a key role in expanding knowledge and developing deep understanding of scientific concepts and principles.

1.2. Simulation

The research investigated inquiry learning within a physics simulation environment. The purpose of using a simulation was to provide an interactive representation of the physics of waves and an active learning environment where learners could explore, interact, and examine various properties of waves such as amplitude, frequency, period, wavelength, and speed in a simulated learning environment.

Research shows that simulations are well-suited for science inquiry learning since they facilitate observation, experimentation, collecting evidence by manipulating inputs, observing the corresponding outputs, and making inferences about causal relations (Hajian et al., 2019; Hajian et al., 2021; van Joolingen & de Jong, 1997). Inquiry exercises or tasks that prompt students to confront their own predictions with experimental results have proven to be more effective than lectures at addressing flawed mental models and misconceptions (Kennedy & de Bruyn, 2011). I therefore selected a simulation to investigate the effectiveness of feedback and self-explanation on acquisition and application of new principles as well as transformation of inaccurate alternative conceptions during the experiment.

I selected the physics of waves as a topic since the basic properties of waves and their relations is a common introductory physics topic with several well-documented counterintuitive concepts. Research has indicated that learning counterintuitive concepts can be highly challenging for students and often requires conceptual change (Brookman-Byrne et al., 2018).

Many researchers have conducted studies that elicit students' alternative conceptions related to speed-medium and sound propagation principles describing wave phenomena. The results indicate that most students at introductory college levels are unable to interpret common sound wave phenomena and have no coherent model of the physics of waves. This study builds on the previous sound wave learning research and focuses specifically on how using self-explanation prompts and elaborative feedback enable student misconceptions about waves to be extracted, encountered, and remediated.

1.3. Statement of the Problem

Sometimes learners fail to create suitable links between their prior and new information due to the inaccuracy or insufficiency of the existing knowledge. In these conditions, learning can become highly challenging, confusing, and difficult. For example, many students may struggle with the concepts of range and spread in statistics as they are often employed interchangeably to refer to variability in daily conversations (Kaplan et al. 2009).

Research shows self-explanation is efficacious for activating prior knowledge and identifying faulty mental models and knowledge gaps (Chi et al., 1994). As Roy and Chi (2005, p. 272) argue, "self-explanation is a domain general constructive activity that engages students in active learning and ensures that learners attend to the material in a meaningful way while effectively monitoring their evolving understanding." However, "the impact of self-explanation on learning is constrained by the content of learners' explanations" (Rittle-Johnson & Loehr, 2017, p. 1502).

According to Smith et al. (1994), to remedy interference of misconceptions, instructional interventions should help learners realize the distinction between their existing misconceptions and the intended expert concepts. Understanding this gap is of considerable importance as it allows the learner to value the existence of the expert concepts alongside the other concepts. This rational competition between misconceptions and corresponding expert concepts is necessary for establishing a framework for comparing the validity of the competing ideas (Strike & Posner, 1985).

In this dissertation, I provide evidence that tutor elaborative feedback is a powerful instructional intervention for repairing misconceptions and bridging the gap between prior understanding and the new intended knowledge. As Sadler (1989) argues, feedback is essential for filling this gap by enhancing the learner's knowledge and reducing the distance between current understanding and correct structural understanding. Students require feedback to discover whether their knowledge is correct, whether it needs to be corrected, and how it should be corrected.

Despite the vast literature on feedback, it appears not much research has been done on the role of tutor feedback in combination with self-explanation prompts within simulation environments where the dynamic graphical representations of the content effectively convey a great deal of information about the phenomenon under study. To the best of my knowledge, relatively little is known about the role of feedback during inquiry learning within an interactive and visually dynamic environment.

Considering participants received real-time response feedback from the simulation while interacting with the embedded components (e.g., using tools such as graphs and measuring tools to test relationships and patterns), it was essential to research what type of external feedback (tutor feedback) would be required for learners to overcome their persistent misconceptions, inaccurate assumptions, and incomplete knowledge.

I guided students through carefully designed tasks and challenged them to explore, test, and explain their thinking and rationale. I employed three types of feedback – no feedback (NF), knowledge of results feedback (KRF), and elaborative feedback (EF) – to investigate the change in the level of understanding and knowledge gain of the participants.

Self-explanation questions (i.e., prompts) such as "Why do you think there is a relationship between variable X and Y?" and "How do you explain the differences between the resulting phenomena of A and B?" were provided as predetermined written prompts, embedded within each activity for all three groups. For example, at the beginning of the first task, the participants in all groups responded to a question prompt eliciting a prediction along with its explanation (e.g., “What do you predict about the relationship between frequency and wavelength in the simulation? Please explain.”). After performing the task, another question prompt was provided to elicit justification for the investigated relationships (e.g., “Was your prediction right or wrong? How do you justify the accuracy of the investigated relationship between frequency and wavelength?”).

The treatment groups were differentiated based on the level of feedback received as an intervention – NF, KRF, and EF. Knowledge of results feedback, also referred to as verification feedback, is “binary information describing whether or not results are correct (acceptable relative to externally defined criteria)” (Butler & Winne, 1995, p.250). Elaborative feedback included verification and provided more information and examples about (a) the topic of the task, (b) the learner response, and (c) errors.

1.4. Research Questions

Participants were given a pretest and posttest on five fundamental concepts of wave physics, four of which are often difficult to learn due to persistent misconceptions. There were two research questions:

1) For learners with low prior knowledge of wave physics, what are the relative effects of NF, KRF, and EF on acquisition of concepts that are not prone to persistent misconception?

2) For learners with low prior knowledge of wave physics, what are the relative effects of NF, KRF, and EF on acquisition of concepts that are prone to persistent misconception?

Chapter 2.

Literature Review

This research draws substantially from meaningful learning theory, self-explanation theory, and theories of feedback intervention. The present chapter identifies relevant aspects of these theories and describes how they come together in the thesis research.

2.1. Meaningful Learning Theory

According to the meaningful learning theory, learning occurs when students are actively engaged in the construction of their own knowledge by assessing the accuracy and capacity of their existing knowledge and integrating the received information into theiryou cognitive structure (Ausubel, 1968; Mayer, 1979, 2002; Novak, 2002).

Schemas, the mental structures that organize memory, are crucial to meaningful learning because if they are limited or faulty, the process of assimilation of knowledge either fails or takes place with error (Chen et al., 2007). In such cases, identifying and repairing misconceptions are essential for schema reconstruction (i.e., accommodation) and meaningful reception learning (Novak, 2002).

Theorists do not fully explain how these faulty schemas arise, but there is a large body of evidence indicating such alternative models can significantly interfere with the process of selection, organization, and integration of knowledge (Mayer, 1999) and may, at some point, substantially interrupt knowledge acquisition (Hewson & Hewson, 1984).

One way to facilitate schema construction and the reconstruction of faulty or invalid schemas is by presenting learners with meaning-making writing tasks that are based on investigating, testing, recording, and reporting results (Fry & Villagomez, 2012). These tasks, which are based on prompting learners to investigate and explain content relative to an authentic context, incorporate many of the criteria that enhance learning such as abstraction, articulation, explanation, reflection, and inference making. Performing such tasks followed by writing outcomes in scientific format promotes thinking and concept formation as it requires learners to explicitly articulate content in their own words. The produced writing by the learner can also function as an indicator of understanding or misunderstanding of the content (Halim et al., 2018) as it is drawn from the learner's previous knowledge and experiences (Ferguson, 2007). This expressed knowledge is highly significant to a tutor for probing the quality and quantity of learners' prior knowledge in relation to the to-be-learned content and taking appropriate actions such as providing suitable information and feedback. That is why structured tasks, with requirements of writing hypotheses, relationships, patterns, and conjectures, were implemented as one of the main components of learning in this study.

Although research shows that scientific inquiry writing tasks are effective in promoting understanding domain principles and concepts, further support is needed to assist learners to understand their conceptions/misconceptions from various perspectives (Finkenstaedt-Quinn et al., 2017) and consequently reinforce or revise their knowledge.

Research shows that prompting learners to recall their relevant prior knowledge through referencing some specific questions, namely focus questions, can provide a specific context for activation of knowledge and learning (Novak & Cañas, 2006). For example, by asking prediction and justification questions, we can provide effective scaffolding for assessment of accuracy and coherence of reasoning of the learner (Nokes et al., 2011; Lim et al., 2010) as well as enabling cognitive and metacognitive processes that facilitate meaningful construction of knowledge (Gurlitt & Renkl, 2010).

Incorporating questions eliciting self-explanation functions as a scaffolding tool not only for identification of existing mental models but also for detecting any knowledge discrepancy gap by explicitly indicating the major similarities and differences between the new ideas and the previously learned ideas (Chi, 2000). Additionally, explanatory questions have been found to boost knowledge transfer (Hajian, 2019; Mayer, 1979; Rittle-Johnson, 2006). Such questions should be provided before, during, and after tasks/activities to direct the learner's attention to the fundamental principles and key relationships within the to-be-learned material.

This research builds on the findings from prior research that self-explanation prompts are effective learning tools that allow learners to engage with the presented information by employing their existing knowledge to predict, justify, and explain new phenomena. The rationale for using self-explanation prompts to induce knowledge activation is rooted in cognitive learning theories describing the processes of self-explanation and meaningful learning. The following section briefly explains how generating explanations for oneself can lead to cognitive and metacognitive benefits.

2.2. Self-explanation

Empirical research in learning and cognitive development has consistently found that the process of explaining to oneself can improve learning, retention, and transfer of knowledge to authentic contexts. This phenomenon, which is known as the self-explanation effect, has been demonstrated in many domains such as acquiring knowledge about physics principles (Chi et al., 1989), biological concepts (Chi et al., 1994), mathematics (Rittle-Johnson et al., 2017), chemistry (Villalta-Cerdas & Sandi-Urena, 2014), and clinical reasoning (Chamberland & Mamede, 2015).

Why is the process of self-explaining so beneficial for learning and understanding? Given the diverse nature of the mechanisms that regulate learning, it is hypothesized that self-explanation enhances learning through processes such as metacognitive monitoring, assimilation, reorganization of knowledge, and deliberate revision of existing mental models of particular domains (Chi et al., 1994; Bisra et al., 2018; Rittle-Johnson et al., 2017; Roy & Chi, 2005). Generating explanations has been found to boost causal reasoning and conceptual abstraction (Bisra et al., 2018; Lombrozo, 2006; Wellman & Liu, 2007).

Self-explanation is therefore an active, constructive process in which the learner creates knowledge and meaning through selection, organization, and synthesis (Chi et al., 1994; Gershman et al., 2009; Lombrozo, 2006; Mayer, 2010). High quality self-explanations involve cognitive elaboration and inferencing such that more information can be extracted from provided learning materials (Chamberland & Mamede, 2015).

A recent meta-analysis on self-explanation found that significant learning gains can be achieved as a result of prompting explanations compared to receiving explanations or simply reviewing material, with a mean weighted effect size of $g = 0.55$ (Bisra et al., 2018). The authors observed that “inducement to self-explain offers benefits similar in magnitude to interventions such as mastery learning (*d* = .50) and peer tutoring (*d* = .55)" (p. 718).

There is ample evidence that generative exercises, such as self-questioning and self-explanation, can activate prior knowledge and encourage predictions, reasoning, and learning (McDermott & Redish, 1999; Kennedy & Bruyan, 2011). Explaining will therefore guide learners to interpret observations in terms of unifying regularities and result in generalization of patterns or principles explained. Discovering and explaining such generalizations can facilitate transfer from one learning context to other relevant contexts (Williams & Lombrozo, 2010).

In this study, participants were asked to self-explain concepts, principles, and relations embedded in simulation inquiry tasks, and record their explanations in writing. The self-explanation questions given in each task prompted learners to actively think ahead and make predictions about principles, properties, and relationships before they engaged with the simulation. The self-explanation questions also prompted learners to justify their reasoning and rationale for more complex and higher-level thinking after engagement with the simulation.

Although the effectiveness of self-explanation on learning is well-documented, self-generated reasoning can also hinder learning if the learner holds false beliefs. This is because our interpretations of the world and inferences are founded on our assumptions (Dellantonio & Pastore, 2020; Hajian et al., 2019). If those assumptions are false, our explanations can also be false. For example, the fact that resistors having different resistance in series circuits carry the same current can rarely be explained accurately (Hajian et al., 2021) if learners believe resistors are like rocks in a hose slowing down the flow of water.

Self-explanation engages learners in constructive activities such as metacognitive monitoring, strategy reflection, and mental model revision. Although these activities often promote deeper learning, they can fail to facilitate learning if the learner has flawed mental models and false assumptions that are mistakenly considered to be error free, coherent, and logical. In this case, self-explanation alone is not sufficient to repair faulty conceptions as the learner has insufficient prior knowledge and informational resources (e.g., diagrams, graphs, and texts) to resolve the encountered unfamiliar information that is contradictory to their existing schema. Previous research shows that novice learners with insufficient or partly incorrect prior knowledge cannot explain how to solve a problem with high intrinsic cognitive load (Paas & Van Gog, 2006; Sweller et al. 1998). Such learners may need to acquire accurate knowledge by studying worked examples before they can independently generate an accurate explanation of the problem solution (e.g., Booth et al., 2013; Kalyuga et al. 2001).

As Roy and Chi (2005) argue, self-explanation can lead to successful learning if it is based on a domain principle or reasoning (high quality explanation) or it can lead to poor learning if it is superficial and erroneous (low quality explanation). I hypothesize that providing appropriate information in the form of feedback may benefit learners in understanding why their explanations are inaccurate or faulty, and how the cognitive dissonance created by these faulty models can be resolved.

In the present study, self-explanation prompts were employed in a physics simulation where students received sufficient knowledge about the basic properties of the fundamental concepts and obtained real-time feedback through interacting with the simulation environment.

2.3. Feedback

2.3.1. Definition of Feedback

Feedback has been defined and conceptualized differently by various researchers. For example, Hattie and Timperley (2007) defined feedback as “information provided by an agent regarding aspects of one's performance or understanding” (p. 81). The provided feedback can therefore reduce the gap between the current and intended learning outcomes. Winne and Butler (1994) suggested that “feedback is information with which a learner can confirm, add to, overwrite, tune, or restructure information in memory, whether that information is domain knowledge, meta-cognitive knowledge, beliefs about self and tasks, or cognitive tactics and strategies'' (p. 5740). This study defines tutor feedback as the information provided by an external agent, such as an instructor, a coach, or a tutor to confirm, disconfirm, correct, improve, and optimize learner comprehension of the intended learning concepts when interacting with new scientific concepts, rules, and principles. According to this definition, an expert tutor provides appropriate information when the learner expresses their current state of task-relevant knowledge. This information, or feedback, may take the form of factual propositions, examples, and/or analogies.

In general, the effects of feedback on learning are positive, powerful, and significant although various types of feedback (e.g., focused on effort, strategies, tasks, outcome, speed, etc.) exhibit substantial variability in their effects under different conditions (Kluger & DeNisi, 1996).

Feedback can also have negative effects on learning under some conditions (Fyfe et al., 2015; Hays et al, 2010; Kluger & DeNisi, 1996). For example, in the complete absence of knowledge and understanding about a specific topic, feedback can be unproductive as it would not help the learner with the process of knowledge integration, i.e., relating the new information to the existing knowledge (Kulhavy, 1977). As Fyfe et al. (2015) argue, if feedback is overly elaborated, incomprehensible, or challenging to process, it may lead to greater cognitive load and less fruitful learning. Feedback is generally constructive when it directs learners' attention to invalid interpretations constructed by the learner based on the principles previously acquired (Hattie & Timperley, 2007).

Feedback is regarded as one of the most fundamental conditions for learning (Kleij et al., 2015) if it allows learners to detect errors, overcome learning obstacles, and apply appropriate strategies for solving problems in the process of learning. The aim of feedback should often be to assess, simplify learning challenges, and repair incorrect interpretations. The ideal feedback provides flexible and customized forms of information needed to stimulate the cognitive processes that lead to revisions of learners' mental models (Azevedo & Bernard, 1995). According to the latest meta-analysis (Wisniewski et al., 2020), the overall effect of feedback on student learning is medium, $d = 0.48$. The effectiveness of feedback is substantially higher when it provides detailed information rather than only knowledge of results. In their meta-analysis, Van der Kleij et al. (2015) presented evidence that elaborated feedback produced a substantially higher effect size ($d = 0.49$) than knowledge of results feedback ($d = 0.05$).

Minimal or mis-targeted feedback may thus lead to frustration, confusion, and lack of understanding in learners (Moreno, 2004). In fact, if feedback is solely focused on student learning outcomes and their final products, it can rarely improve the process of learning and application of learned concepts (Paulson Gjerde et al., 2017).

2.3.2. Types of Feedback

Feedback, depending on the type of information it contains, addresses various aspects of learning. For example, feedback may provide information at personal, task, process, and/or self-regulatory levels. It can also be characterized based on its degree of cognitive complexity (Wisniewski et al., 2020; Hattie & Timperley, 2007).

Information within feedback can be as limited as verifying the accuracy of a response to a question, problem, or task or as elaborated as explaining in detail about specific errors, misconceptions, and the way concepts and principles need to be addressed and assimilated (Azevedo & Bernard, 1995; Hattie & Timperley, 2007; Shute, 2008).

Feedback can be classified into various types (Shute, 2008) such as knowledge of results feedback (KRF) and elaborative feedback (EF). KRF indicates whether the answer or process is correct or incorrect but does not provide the correct answer or any additional information. According to some researchers, “its main purpose is to reinforce the correct recall of facts” (Kleij et al., 2015, p. 477). In the early years of feedback studies, KRF was often interchangeably used for feedback as it served the two goals of informing about the correctness of the produced outcome (Fyfe et al., 2015) and characterizing the quality of the work performed by the learner (Sadler, 1989).

KRF is not considered very effective by many researchers (Jaehnig & Miller, 2007) due to its lack of information about how to improve. KRF is provided as one treatment condition in this study because (a) it may be more effective in the context of simulation-based learning where it complements feedback received from the simulation as the learner explores, tests, and observes, and (b) when contrasted with the EF treatment condition it allows analysis of which feedback features contribute to learning.

EF is highly informative, intentional, and targeted. According to Shute (2008), EF can take many forms, such as analogies, examples, hints, additional information, and more detailed explanation of the correct answer. Since the term EF has a wide range of possible meanings, the degree to which EF is effective for learning purposes varies extensively. EF is most simply outcome accuracy information (KRF) which can be elaborated by more detailed information such as causal explanations, analogies, supporting and counterexamples. EF may also provide information about learning processes.

Moreno and Mayer (2005) noticed that students learned better from a computer-based game called Design-a-Plant if they received explanatory feedback on their move rather than corrective feedback or no feedback. Renkl (2002) also found that students learned to solve mathematics problems better when they received a detailed explanation for each step they performed in an interactive computer-based lesson. Students can learn more productively with explanatory rather than corrective feedback alone (Moreno & Mayer, 2005). Additionally, they can transfer their knowledge more flexibly resulting in superior performance on new inference questions (Butler et al., 2013).

In this study, two types of feedback were provided. Knowledge of results feedback (KRF) which was limited to verification of correctness of the explanation provided by the participant (Butler & Winne, 1995). Elaborative feedback (EF) consisted of knowledge of results as well as an explicit, detailed explanation of relevant scientific theories and reasoning.

2.3.3. Timing of Feedback

Given the significance of feedback in learning, it is essential to know when it needs to be delivered to produce effective outcomes. In the meta-analysis conducted by Kulik and Kulik (1988), results of applied studies generally favored immediate rather than delayed feedback. On the other hand, Butler et al. (2007) argued that delayed feedback can lead to much higher test performance compared to immediate feedback.

The debate on whether immediate or delayed feedback is more effective has been challenged by the inconsistent definitions given by different researchers. For example, immediate feedback has ranged anywhere from a second after a task to the same day. Similarly, delayed feedback is defined anywhere between 10 seconds after completion of a task to as much as a week later. The lack of a definitive timescale distinguishing each type of feedback makes research on feedback timing highly inconsistent.

It is argued that the terms delayed and immediate are relative and, whether delayed or immediate, productive feedback is informative and customized to the needs of the learner (Narciss, 2008). The efficacy of feedback is determined by many factors such as the complexity of the concepts, the experience of the learner, and the characteristics of the environment. Therefore, the timing of feedback should ensure that the feedback is processed and attended to by the participants whether that feedback is given immediately or at a delay.

In this study, students received immediate real-time feedback from the simulation while interacting with the relevant components, tools, and variables. They were initially given some time to conduct the provided structured tasks and prompted to be immersed in their own learning by observing, testing, collecting data, and investigating patterns. After writing their own explanations in response to the given questions, they immediately received feedback from the tutor.

2.4. Theoretical Motivation

In physics education settings, it has been repeatedly observed that traditional techniques such as lectures and demonstration methods are insufficient for correcting students' existing incorrect conceptions (Chi et al., 1994; diSessa, 1996). Thus, constructive learning strategies such as self-explanation, which are theorized to promote inference generation, information integration, and causal connections seem to be beneficial in filling in the missing information (Roy & Chi, 2005).

Although self-explanation is generally an effective instructional strategy (Bisra et al., 2018), several studies found that self-explanation was not effective by itself because it added extraneous cognitive processing to learning (Adams & Clark, 2014). For example, in the Design-a-Plant simulation study, Moreno and Mayer (2005) found students who self-explained showed no significant benefit over students who did not. However, students who self-explained performed significantly better when provided with elaborative feedback providing logical reasons and examples. Research has shown that feedback can play a significant role in a variety of learning contexts (Hattie & Timperley, 2007; Sadler 1989; Shute, 2008; Wisniewski et al., 2020) such as natural classroom settings (Hannafin, 1982), web-based environments (Smits et al., 2008), simulation contexts (Moreno & Mayer, 2005), and learning games (Johnson et al., 2017; Mayer & Johnson, 2010).

Feedback may therefore act as a complementary instructional strategy that improves the effectiveness of self-explanation. While each strategy is known to be individually effective in facilitating conceptual and procedural learning (Nokes-Malach et al., 2013; Rittle-Johnson et al., 2009) as well as promoting active learning (Chamberland & Mamede, 2015), they may be especially powerful in combination because each provides elements that the other lacks.

Why were feedback and self-explanation combined in this study? Piagetian learning theory is founded on the premise that generation of knowledge and creation of meaning are directed by one's prior knowledge and immediate experience and are driven by the learner's motivation to resolve inconsistencies between them (Posner et al., 1982; Wang & Andre, 1991). There are two central learning processes within Piagetian constructivism, accommodation and assimilation. Assimilation is the process of incorporating new information into our existing schemas. Assimilation requires an understanding of how the new information connects to the pre-existing principles and how coherently the new knowledge can explain the new phenomenon. On the other hand, accommodation is necessary when the learner's cognitive structure is not suitable for integrating the new information (Vinner, 1988; Wang & Andre, 1991). Sometimes, our existing schema undermines the acquisition of new knowledge and needs to be restructured to accommodate the new concepts.

Schemas can either help a learner acquire knowledge or impede the learning process by determining what can or cannot be understood (Ausubel, 1968; Zhiqing, 2015). Knowledge construction activities such as self-explaining and reasoning allow learners to monitor their understanding, potentially improve their comprehension, and assist tutors to determine which learning process needs to occur. "The integrative nature of deep-level reasoning questions presumably activates relevant schemas of various sorts, and this activation makes new content easier to process and map onto existing knowledge structures" (Gholson & Craig, 2006, p. 121).

Tutor-questioning allows learners to perform memory search, challenge existing mental models, and identify cognitive needs, whereas successful feedback provides the information required for filling knowledge gaps and connecting diverse bits of knowledge into one coherent piece of knowledge and deep understanding.

This study investigates the extent to which feedback bears a complementary relationship with self-explanation. Feedback is required for recognizing cognitive barriers and replacing them with intelligible information as it provides an opportunity for the learner to compare their own mental models with an expert model. As Bangert-Drowns et al. (1991) argue, feedback allows learners to evaluate their responses and make adjustments to their knowledge, beliefs, and conceptions according to the new model if feedback is mindfully processed. Therefore, feedback functions as a tool to facilitate accurate abstraction and inference generation. On the other hand, self-explanation prompts are a means for eliciting learners' related prior knowledge and evaluating the level of complexity and accuracy of this knowledge.

Learner responses to self-explanation prompts can reveal whether current schemas are inhibiting, insufficient, or fragmented in relation to understanding of the target material. At this stage, providing feedback that includes explanations, elaboration, examples, and analogies may enable learners to expand their knowledge, fill their knowledge gaps, and reconstruct their incomplete mental structure (Piaget, 1968).

The main motive for this study was lack of empirical research on the effectiveness of combining self-explanation and feedback in correcting learners' misconceptions and improving their knowledge gain in a physics simulation environment. This study investigated the effects of two types of feedback (KRF & EF). The goal was to determine the most effective type of feedback necessary for identifying and eliminating scientific misconceptions and replacing them with correct scientific models. It is hypothesized that a combination of self-explanation and feedback can guide and direct learners in the process of scientific model construction and optimize acquisition of scientific concepts (Stevenson et al., 2009).

Chapter 3.

Methodology

3.1. Participants

Not knowing what frequency distributions would be obtained and which type of inferential test would eventually be applied, the minimum sample size was determined by an a priori power analysis using the G*Power 3.1 (Faul et al., 2007). Inputting effect size $d = 0.50$, $\alpha = 0.05$, and power = 0.95 returned a recommended minimum of $N = 66$. A sample size of 66 to 76 participants was therefore planned.

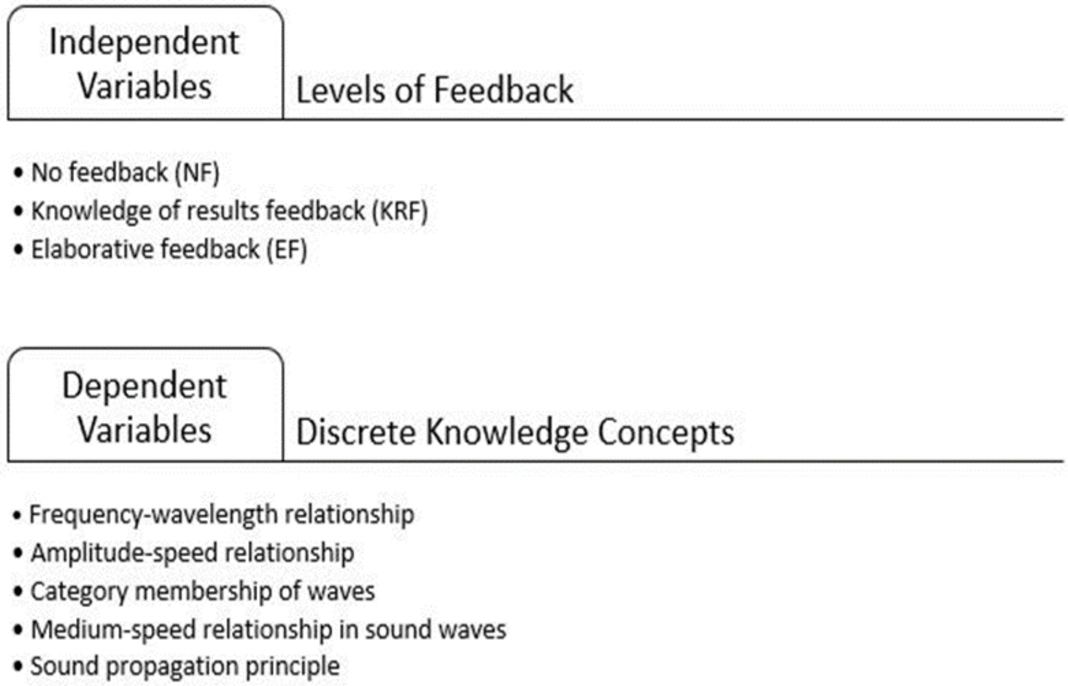
Seventy-six undergraduates attending Simon Fraser University volunteered to participate. They were recruited by posters placed around campus and were able to book their participation using an online scheduling system (SimplyBookMe). Each was paid $15 to participate in a one-hour session.

An a priori decision was made that only individuals who demonstrated low prior knowledge on a pretest (see Appendix B) about the physics of waves would be included in the study. Pragmatically and scientifically, I was only interested in how low prior knowledge learners would respond to the interventions. A criterion of ≤ 50% was selected because it (a) implied a fairly low level of knowledge and (b) was high enough that participants could be recruited with reasonable efficiency. As a result, seven participants were excluded from the study. Further topic-wise exclusions performed at the analysis stage are described later.

3.2. Design

A pretest-posttest, between-subjects design was employed to investigate the efficacy of three different treatments: no feedback (NF), knowledge of results feedback (KRF), and elaborative feedback (EF). Participants' knowledge gain on five distinct concepts of physics was calculated from their performances on the pretest and posttest. The five measured variables were: frequency-wavelength relationship, amplitude-speed relationship, category membership of waves, medium-speed relationship, and applying the sound propagation principle in authentic contexts (Figure 3.1).

Figure 3.1 Layout of the Experiment



The 68 retained participants were randomly assigned to the three conditions of NF (*n* = 24), KRF (*n* = 22), and EF (*n* = 22). All three conditions were provided with inquiry activities conducted within a computer-based simulation environment and self-explanation prompts embedded in the tasks. Therefore, each participant, regardless of the experimental condition, had the same opportunity to interact with the simulation and receive real-time feedback from the simulation as a result of manipulating variables, observing visual properties of the waves, utilizing measuring tools, and selecting/deselecting simulation features such as air particles, graphs, and speaker sound.

3.2.1. Treatment Conditions

The intervention was feedback provided by the researcher, referred to as tutor feedback. Tutor feedback was provided at three levels of none (NF), knowledge of results (KRF), and elaborative (EF). KRF was either “Yes, your answer is correct." or “No, your answer is incorrect.” Some other examples of KRF were: “That’s exactly what it is.”, “Yes! You got it.”, “Not quite actually.” or “That’s not what’s happening here.” EF consisted of KRF as well as further explanation about why the learner response was correct or incorrect along with real life examples. Some examples of EF are: “You said A and B are positively related. This answer is incorrect. That is because when variable A decreases or increases variable B does not change. Therefore, A and B are not related.” or “You’re right! Frequency and wavelength are inversely related. Look at the motion of the water waves and the corresponding graphs in the simulation, waves with higher frequencies have shorter wavelengths and waves with lower frequencies have longer wavelengths. In other words, when one increases, the other one decreases and vice versa.”

To decrease the impact of confounding variables such as task time, types of self-explanation prompts, feedback contents, and simulation instructions, all groups received identical tasks within the same time frame, the same supplementary material in the form of one informational handout, printed self-explanatory prompts in sequential form (prediction followed by justification), and clear explanation about the simulation features and tools. Participants were individually monitored during the entire session.

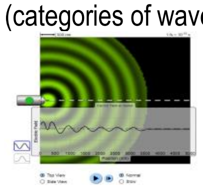
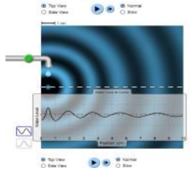
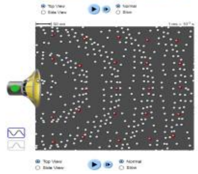
3.3. Instruments & Materials

The experiment consisted of four phases: a pretest, inquiry tasks, an immediate posttest, and a structured interview.

3.3.1. Pre and Post Tests

The pretest and posttest were identical with five distinct items, each testing a basic concept of wave physics exhibited within the simulation (see Table 3.1). Each item had a five-option multiple choice format and an explanatory short answer question (Appendix B). The main purpose of the multiple-choice component was to provide participants with keywords they could use in their short answer explanation. Students’ responses to the paired MC and SA questions, which functioned as a micro test for each concept, consistently demonstrated the same level of knowledge of a specific concept. In each case, the paired questions returned the same result. Therefore, only MC scores were used for further data analysis.

Table 3.1 Topics of Knowledge Tested in Pretest and Posttest

Questions	Content	Category of Knowledge	Required Knowledge
Question 1	Relationship between two variables of frequency (f) & wavelength (λ)	Relational understanding: linear relationship between x and y	A linear relation between two variables of x and y can be positive, negative, or zero. Frequency and wavelength are inversely related (negative relation).
Question 2	Relationship between speed & amplitude	Relational understanding: (misconception: higher amplitude means higher speed). In fact, both Wave A and Wave B travel at the same speed. 	The amplitude of a wave does not affect the speed at which the wave travels. The speed of a wave is only altered if properties of the medium through which it travels are changed.
Question 3	Differences in properties of three waves of light, sound, and water (categories of waves)   	Misconception: all waves behave the same way as they all display similar properties such as amplitude, frequency, wavelength, and period. In fact, waves can be fundamentally different (electromagnetic vs mechanical waves).	All waves have the same fundamental properties. However, some waves (e.g., water waves and sound waves) are formed through vibration of particles and therefore they require a medium to propagate but light waves do not require a medium to propagate.

Questions	Content	Category of Knowledge	Required Knowledge
Question 4	The speed of sound depends on the elasticity and density of the medium through which it is traveling.	Misconception: Sound waves travel faster and more effectively in air than in liquid and solids. In fact, sound travels fastest through solids. This concept is particularly hard to believe since our general experiences lead us to hear reduced or garbled sounds in water or behind a solid door.	The greater the elasticity and density, the faster sound travels in a medium. Therefore, the speed of sound is higher in aluminum than in air and water.
Question 5	Sound cannot travel in the empty vacuum of space because sound waves need a medium to vibrate through such as air.	Misconception: Sound can become quieter but not silent. In fact, when there is no air, there is no sound in the jar.	Sound vibration travels through matter. So, no one can hear you scream in space because there is no air in the vacuum of space to transfer the sound.

As indicated in Table 3.1, identifying students' knowledge about waves and detecting their misconceptions before performing the inquiry activities was the major focus of the pretest. These questions, which have been repeatedly employed by other researchers (Wittmann et al., 1999; Pejuan et al., 2012), revealed that almost all participants had very limited prior knowledge about the presented topics.

It is worth mentioning that volunteers for this research were mostly registered in non-science university programs and were expected to have limited knowledge of wave physics. Many participants mentioned that their knowledge of scientific experiments was due to their high school science coursework.

3.3.2. Supplementary Reading

All participants were given an informational handout at the beginning of the session (Appendix C). The supplementary reading used definitions and diagrams to present concepts prerequisite to understanding the tasks and activities during the experiment (e.g., wave properties and various structures of matter). Participants were invited to ask questions in case of any ambiguity regarding the provided information.

3.3.3. Tasks

The tasks consisted of four inquiry activities fully explained on a sheet referred to as the task sheet (Appendix A). The summary of these activities is also provided in Table 3.2.

Each activity aimed at a specific target concept and divided into three subsections of prediction prompt, practice-with-simulation questions, and justification prompt (Table 3.2). The practice-with-simulation questions (mini tasks) allowed learners to examine the details of each task. Since self-explanation questions were part of the inquiry tools in this experiment, all groups received identical prompts and were guided to write their explanations clearly within a specific period of time (10 minutes).

Each task required observation, prediction, generating results by interacting with the simulation, and justification. The prediction prompt acted as a pre-simulation engagement activity to elicit learners' relevant existing knowledge whereas the justification prompt was a post-simulation engagement explanation to elicit their level of understanding of the target material (Gershman et al., 2009). Both of these prompts were delivered in written form within the context of each task.

This study only addressed the effects of prompted self-explanation and not the effects of spontaneous self-explanation as research provides evidence that students who are prompted by an instructor/tutor often learn more than those who are not (Chi et al., 1994).

Table 3.2 Task with Four Inquiry Activities

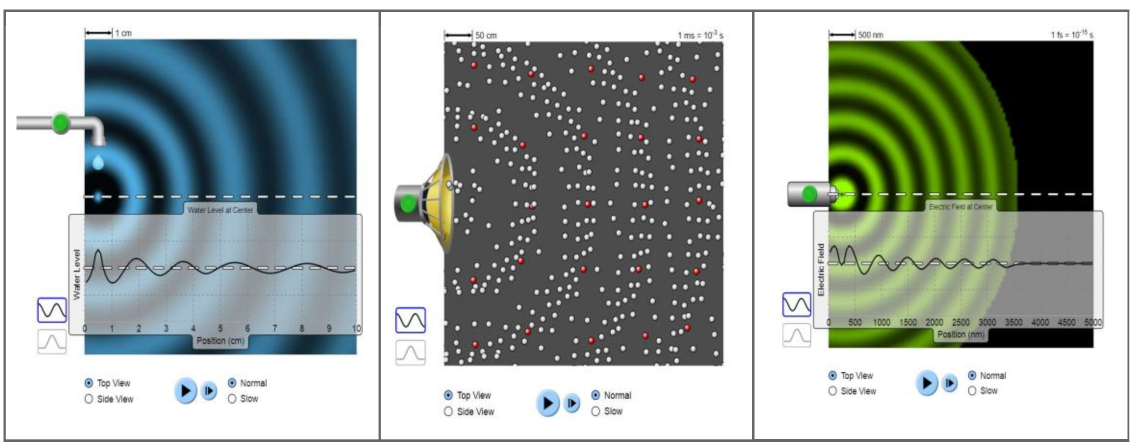
Task	**Purpose**	**Section A** Prediction Prompt	**Section B** Justification Prompt
Activity A	Investigating how changing amplitude and frequency affects the shape, size, and intensity of water waves	Predict what happens to the size, shape, and the intensity of the color of the water waves when the following variables change Amplitude Frequency	Do you think the same relationships hold in light, water, and sound waves? Justify your explanation.
Activity B	Investigating the relationship between frequency and wavelength in all kinds of waves	What is the relationship between Frequency (f) & Wavelength (λ)? Is this relationship direct (positive) or inverse (negative)?	Please explain why this relationship is positive or negative.
Activity C	Investigating the relationship between frequency, amplitude, wavelength, and speed of the wave	What factors do you think affect the speed of the sound waves and why?	Was your prediction right or wrong? Explain your observation and justify the investigated patterns.
Activity D	Investigating the relationship between the speed of sound waves and the properties of the medium they travel through	How do you predict the speed of sound in air compared to water? (*Before-the-fact explanation*)	The speed of sound in air is approximately 343 m/s at normal room temperature while the speed of sound in water ranges from 1450 to 1498 meters per second. Considering the different structures of liquids and gases in the handout, how do you explain this difference? (*After-the-fact explanation*)

3.3.4. Simulation

The PhET Waves simulation was selected for this study (Figure 3.2). The simulation allowed learners to engage with the concepts and relations in the domain of wave physics and receive instant graphical and numeric feedback from the simulation (Slavin et al., 2014; Veermans & Jaakkola, 2019).

The simulation allowed learners to employ virtual hands-on activities such as manipulating multiple variables and features to produce different behaviours and outputs. These activities generated opportunities to observe patterns and discover rules and relations according to the given tasks. For example, in the first activity, variables such as amplitude, frequency, wavelength, period, and speed were manipulated and measured under various conditions and the results of their changes were compared for three types of waves: light, sound, and water.

Figure 3.2 Screenshots of PhET Intro to Waves Simulation



Note. https://phet.colorado.edu/en/simulation/waves-intro

3.3.5. Interview Questionnaire

After completing the posttest, participants received a questionnaire consisting of four items. The purpose of this written interview was to gather information about the participants' learning experience, their opinions about the difficulty level of the material and activities, the amount of learning that occurred according to the participants' perspectives, and finally their suggestions for the researcher with regard to the level of guidance provided in the study. Some of these perspectives will be presented in the discussion section. However, a detailed qualitative analysis of the collected interview data will be the subject of future research.

3.4. Procedure

3.4.1. Ethics

The study was part of the Coaching Discovery Learning project, which received approval from the Simon Fraser University Research Ethics Board (REB). A detailed consent form was signed by each participant at the beginning of the experimental session in which the purpose of the study was explained. Participants were encouraged to ask questions and reminded about their right to withdraw from the experiment at any time.

3.4.2. Setting

The experiment was conducted in a laboratory. At the beginning of the experiment, participants were randomly assigned to either the NF, KRF, or EF group and seated at a computer. They read and signed a consent form, and were informed about the goals of the study, tasks, simulation, and the significance of their contribution. Following the introduction, they took the pretest within a time limit of 8 minutes. After completing the pretest and meeting the inclusion criterion of receiving less than 50%, each participant was provided with a randomly assigned experiment ID number to begin the activities. The intention of using the experiment ID number was to protect the anonymity of each participant. The excluded participants were compensated and informed about their option of continuing with the session or leaving.

3.4.3. Protocols & Administration

All four learning activities were described in a task sheet. This sheet (Appendix A) and the supplementary information handout (Appendix C) were provided to the participant after they finished the pretest. The tasks were timed. Each inquiry learning activity was set for a maximum of 10 minutes.

The study consisted of one session which included signing an ethics form, responding to the pretest, reading the handout, performing the inquiry tasks, responding to a posttest, and finally participating in a brief survey. Sessions lasted 60 minutes.

Participants first completed the pretest. Subsequently, they read the supplementary material and performed the inquiry tasks. They were reminded to refer to the given supplementary information if required, ask questions about the simulation and its function, and use the task sheet as a discovery guide. Research shows that simulations can enhance learning if learners are given access to domain information while they perform structured inquiry (de Jong & Van Joolingen, 1998; Honomichl & Chen, 2012).

For every task there was a pre-engagement prompt (i.e., prediction question) and a post-engagement prompt (i.e., justification prompt). Every participant was required to respond to these questions and fully explain their reasoning process in written form. Similar to previous studies (e.g., Lin et al., 2016), prediction prompts were used to induce learner's prior knowledge. And justification prompts were employed to promote coherent reasoning about variables manipulated in the simulation (e.g., characteristics of a wave, frequency-wavelength relation, type of the wave, cycle of the wave, transmission of sound, water, and light waves, and speed of sound wave). Table 3.2 shows examples of such prompts.

The open-ended questioning strategy has shown to be highly effective in identifying errors and conceptual problems – which are also referred to as learner blind spots by (Lee et al., 2018). From a cognitive perspective, one advantage of externalizing outputs is to help learners overcome their cognitive load (Sweller, 1994). From a learning perspective, the externalized outputs become new materials that a student can further examine to infer new knowledge (Chi & Wylie, 2014). From an evaluation perspective, student misconceptions become especially evident in self-generated explanations as they provide rich information about students' understanding or misunderstanding and their knowledge of scientific terminologies (Halim et al., 2018). Research shows this method is more effective than other response assessments in elicitation of knowledge (Parker et al., 2012).

The posttest was administered shortly after the feedback intervention. After the posttest, a questionnaire including 5 multiple choice questions was given to the participants. The purpose of this survey was to collect secondary data for further investigation on feedback. The collected data was not fully analyzed for this study as it did not directly address the research questions of interest.

3.4.4. Intervention

All three groups performed identical assigned tasks and were prompted to predict and justify the target concept or relationship in each learning activity. The NF group received no external tutor feedback. The KRF group received feedback such as “Yes, you are correct” or “Good try! But your response is incorrect,” after generating explanations in response to the written self-explanation prompts. The EF group received verification comments as well as detailed information required for understanding the desired concepts or principles, along with examples and rational explanations. The kinds of information provided in the EF was consistent among all participants – i.e., reasons for the accuracy or inaccuracy of the learner explanations, examples, analogies, and confirmatory questions. For both feedback groups, the corresponding feedback was provided immediately after a participant completed each task, within the given time, and recorded justification for the provided responses. The reason for this timing was to allow learners to spend sufficient time on each activity and be challenged before being provided with tutor feedback.

Chapter 4.

Results

4.1. Test Item Analysis

The pretest-posttest questions were designed to examine different concepts about physics of waves. The inter-item correlations are shown in Table 4.1 and Table 4.2. They were small and not statistically detectable in all but two cases.

Table 4.1 Pretest Items Correlation

	1	2	3	4	5
1. PreQ1	-				
2. PreQ2	-.12	-			
3. PreQ3	.09	-.04	-		
4. PreQ4	-.12	-.03	.04	-	
5. PreQ5	.23	.05	-.19	-.13	-

Table 4.2 Posttest Items Correlation

	1	2	3	4	5
1. PostQ1	-				
2. PostQ2	.08	-			
3. PostQ3	.02	.28*	-		
4. PostQ4	.15	.23	.39**	-	
5. PostQ5	.15	.15	.13	.01	-

*. Correlation is significant at the 0.01 level (2 tailed)
**. Correlation is significant at the 0.05 level (2 tailed)

4.2. Measuring Knowledge Gain

After the initial exclusion described in the previous chapter, the participants all had low prior knowledge (⩽ 50%) as measured by whole pretest scores. Table 4.3 presents the means and standard deviations of pretest, posttest, and gain score for each group with regard to the concepts of frequency-wavelength relation (Q1), amplitude-speed relation (Q2), wave category membership (Q3), medium-speed relation (Q4), and sound propagation principle (Q5).

A secondary, item-wise exclusion was used such that participants who answered a pretest item correctly were removed from the posttest analysis for that item. The gain score was therefore the same as the posttest score and was either zero or one for each retained participant. Table 4.4 shows descriptive statistics after the sample size of each group was reduced by these eliminations. The scores summarized in Table 4.4 were used for all further analysis and interpretation.

Table 4.3 Means and SDs of Pretest, Posttest, and Gain Scores for Each Concept of All Participants

		EF *M* (*SD*)	KRF *M* (*SD*)	NF *M* (*SD*)
Knowledge Category	*N*	24	22	22
1. Frequency-Wavelength Relationship	Pretest 1	0.18 (0.40)	0.27 (0.45)	0.49 (0.5)
	Posttest 1	0.86 (0.35)	0.82 (0.39)	0.87 (0.33)
	Gain 1	0.68 (0.8)	0.55 (0.50)	0.37 (0.58)
2. Amplitude-Speed Relationship	Pretest 2	0.05 (0.21)	0.05 (0.21)	0.00 (0.00)
	Posttest 2	0.77 (0.43)	0.50 (0.51)	0.42 (0.50)
	Gain 2	0.72 (0.45)	0.45 (0.59)	0.42 (0.50)
3. Wave Category	Pretest 3	0.00 (0.00)	0.18 (0.39)	0.00 (0.00)
	Posttest 3	1.00 (0.00)	0.18 (0.39)	0.29 (0.46)
	Gain 3	1.00 (0.00)	0.00 (0.43)	0.29 (0.46)
4. Medium-Speed Relationship	Pretest 4	0.05 (0.2)	0.05 (0.21)	0.00 (0.00)
	Posttest 4	0.68 (0.47)	0.27 (0.45)	0.13 (0.33)
	Gain 4	0.63 (0.49)	0.23 (0.53)	0.13 (0.34)
5. Principle of Sound Propagation	Pretest 5	0.32 (0.48)	0.31 (0.47)	0.45 (0.50)
	Posttest 5	0.55 (0.50)	0.55 (0.50)	0.54 (0.51)
	Gain 5	0.23 (0.53)	0.23 (0.61)	0.08 (0.40)

Note. This table includes all gain scores (i.e., +1, 0, and -1).

Table 4.4 The Mean and SD of Gain Scores for Each Concept After Exclusion of Participants who Demonstrated Knowledge of that Concept on the Pretest

Knowledge Category		EF *M* (*SD*)	KRF *M* (*SD*)	NF *M* (*SD*)
1. Frequency-Wavelength Relationship	*N*	18	16	12
	46	0.83 (0.38)	0.75 (0.45)	0.83 (0.39)
2. Amplitude-Speed Relationship	*N*	21	21	24
	66	0.76 (0.44)	0.52 (0.51)	0.42 (0.50)
3. Wave Category	*N*	22	18	24
	64	1.00 (0.00)	0.11 (0.32)	0.29 (0.46)
4. Medium-Speed Relationship	*N*	21	21	24
	66	0.67 (0.48)	0.29 (0.46)	0.13 (0.34)
5. Principle of Sound Propagation	*N*	15	15	13
	43	0.40 (0.51)	0.47 (0.52)	0.23(0.43)

4.3. Knowledge Gain for Five Distinct Concepts

The null hypothesis for each dependent measure was no association between treatment group and gain score (0, 1). ANOVA was not applicable because the data did not meet parametric assumptions such as normality and homogeneity of variance. The suitability of the Kruskal-Wallis test was also questionable as this test is appropriate for ranks whereas my data were binary. Either the chi-square (χ^2) test of association or Fisher's exact test was used to detect the relationship between treatment and each of the five dependent variables. Among the assumptions of the chi-square test are that at least 80% of the cell expected frequencies must be greater than 5, and none must be less than one (Bewick et al., 2004).[1] I used the chi-square test when that assumption was met. When that assumption was not met, I applied Fisher's exact test to each of three possible treatment comparisons as if performing post-hoc tests. Although it is possible to perform Fisher's exact test on larger contingency tables under certain conditions, its application is usually restricted to 2 x 2 tables.

For the multiple post hoc tests following a chi-square test or when applying Fisher's exact test, I used the Bonferroni adjustment. This adjustment is often used to counteract the problem of Type I error inflation that occurs when multiple comparisons are made. For the three paired comparisons, the α-level of 0.05 was divided by three. Therefore, the p-value returned by each test was compared to the adjusted alpha level of .017.

Cramer's V effect size was used to show the degree to which sample results diverged from the null hypothesis. Table 4.5 shows how Cramer's V was interpreted (Cohen, 1988). Effect sizes assist in assessing the practical significance of the results.

[1] The expected frequency of a cell is calculated as $E_{R,C} = (M_R \times M_C)/N$, where R = row, C = column, and M = marginal frequency.

Table 4.5 Conventions for Describing the Magnitude of Association in Contingency Tables

***V* (*r* = 2)**	
Post hoc	**Interpretation**
.10	Small
.20	
.30	Medium
.40	
.50	Large
.60	
.70	
.80	

Note. According to Cohen (1988, pp. 222 - 227) the interpretation of effect size depends on the smallest of the two dimensions of the contingency table which he denotes as r.

At the threshold of α = 0.017, there was no statistically detectable relationship between the type of intervention and knowledge gain for the concepts of frequency-wavelength, amplitude-speed relationship, and the sound propagation principle (Tables 4.7, 4.8, 4.13). However, there was an association between the type of intervention and knowledge gain for the concepts of wave category (Table 4.9) and medium-speed relationship (4.11), which are common persistent misconceptions. Effect sizes indicated the two detected relationships were strong.

For Q1 (Table 4.6), the data did not meet the assumptions of the chi-square test. The analysis proceeded directly to Fisher's exact test on the three treatment pairs (Table 4.7) which detected no effect of treatment. All the remaining concepts (Q2, Q3, Q4, Q5) met the assumptions of the chi-square test. Effects due to treatment were statistically detected for Q3 (Table 4.9) and Q4 (Table 4.11), but not for Q2 (Table 4.8) and Q5 (Table 4.13).

Table 4.6 Frequency of Gain on Q1
Frequency-Wavelength Relationship

	Zero gain		Positive gain	
Groups	*n*	%	*n*	%
EF	3	16.70	15	83.30
KRF	4	25.00	12	75.00
NF	2	16.70	10	83.30

Note. *N* = 46. Three expected frequencies were less than 5, and none were less than 1.

Table 4.7 Fisher's Exact Test (FET) of Association for Q1 Gain Scores
Frequency-Wavelength Relationship

Comparison	Chi-square	*df*	*p*-Value	FET (*p*)	Cramer's *V*
EF vs NF	.000	1	1.00	1.00	.000
EF vs KRF	.360	1	.549	.681	.103
KRF vs NF	.283	1	.595	.673	.101

Table 4.8 Frequency of Gain on Q2 Amplitude-Speed Relationship

Groups	Zero gain		Positive gain	
	n	%	*n*	%
EF	5	23.80	16	76.20
KRF	10	47.60	11	52.40
NF	14	58.30	10	41.70

Note. $\chi2$ (2) = 5.59, *p* = .061, *V* = .291, *N* = 66. Zero expected frequencies were less than 5.

Table 4.9 Frequency of Gain on Q3 Wave Category Membership

Groups	Zero gain		Positive gain	
	n	%	*n*	%
EF	0	0.00	22	100.0
KRF	16	88.90	2	11.10
NF	17	70.80	7	29.20

Note. $\chi2$ (2) = 37.029, *p* < .001, *V* = .767, *N* = 64. Zero expected frequencies were less than 5.

Table 4.10 Post Hoc Group Comparison for Wave Category (Q3) Gain Scores

Comparison	Chi-square	*df*	*p*-Value	FET (*p*)	Cramer's *V*
EF vs NF	24.718	1	<.001	<.001	.733
EF vs KRF	32.593	1	<.001	<.001	.903
KRF vs NF	1.992	1	.158	.150	.258

Note. FET = Fisher's Exact Test

Table 4.11 Frequency of Gain on Q4 Medium-Speed Relationship

Groups	Zero gain		Positive gain	
	n	%	*n*	%
EF	7	33.30	14	66.70
KRF	15	71.40	6	28.60
NF	21	87.50	3	12.50

Note. $\chi 2$ (2) = 15.008, $p < .001$, $V = .477$, $N = 66$. Zero expected frequencies were less than 5.

Table 4.12 Post Hoc Group Comparison for Medium-Speed Relationship (Q4) Gain Scores

Comparison	Chi-Square	*df*	*p*-Value	FET (*p*)	Cramer's *V*
EF vs NF	13.980	1	<.001	.001	.557
EF vs KRF	6.109	1	.013	.029	.381
KRF vs NF	1.808	1	.179	.267	.179

Note. FET = Fisher's Exact Test

Table 4.13 Frequency of Gain on Q5
Sound Propagation Principle

Groups	Zero gain		Positive gain	
	n	%	*n*	%
EF	9	71.40	6	28.60
KRF	8	65.00	7	35.00
NF	10	87.00	3	13.00

Note. $\chi2$ (2) = 1.736, *p* = .420, *V* = .201, *N* = 43. One expected frequency was less than 5, and none were less than 1.

Chapter 5.

General Discussion

Research shows self-explanation is a highly effective strategy for activating prior knowledge, integrating new and existing knowledge (Roy & Chi, 2005), identifying faulty mental models, and filling knowledge gaps (Bisra et al., 2018; Chi et al., 1989, 1994; Rittle-Johnson & Loehr, 2017; Wylie & Chi, 2014). This domain-independent learning strategy promotes knowledge construction and meaningful understanding through self-monitoring and mental model revision (Roy & Chi, 2005).

Although self-explanation is often viewed as a facilitative constructive learning mechanism in many contexts, the effectiveness of this strategy can be constrained by numerous factors such as prior existing beliefs and domain knowledge, complexity of the target domain, and task difficulty (Bielaczyc et al.,1995; Ionas et al., 2012; Kuhn & Katzz, 2009; Lombrozo, 2006; Nokes et al., 2011; Rittle-Johnson & Loehr, 2017). Research shows explanations based on one's faulty solution strategies or choices may undermine learning (Rittle-Johnson & Loehr, 2017), lead to further cognitive barriers, and hamper information seeking (Savoleinen, 2015). For example, in the study by Kuhn and Katz (2009), the more children used pre-existing theories in their explanations, the more firmly they persisted with and became committed to them.

Explanation does not always result in beneficial effects as "the very properties of explanation that make it a powerful mechanism for learning under some conditions lead to systematic errors under others" (Williams et al., 2013, p.1006). Incorrect assumptions and beliefs must therefore be examined, identified, and corrected for explanations to be effective and learning to be constructive (Kuhn & Katz, 2009; Lombrozo, 2006).

This study introduced tutor feedback as an instructional strategy for potentially optimizing self-explanation. I hypothesized self-explanation without tutor feedback would be inadequate when students held strong misconceptions about intended learning concepts. The findings confirmed this hypothesis and indicated that self-explaining within an interactive simulation environment was insufficient for learning despite the interactively generated information provided by the simulation. Elaborative tutor feedback, presented in the form of knowledge of results and detailed content information, was essential for learning as it created a two-step integrated learning system based on the principles of *diagnosis* and *repair*. First, self-explanation activated knowledge and helped the tutor to detect erroneous mental models. Second, detailed feedback provided knowledge verification, task-process information, and needed content information. These two instructional mechanisms acted as a *gap detector* and *gap filler*. Feedback was most productive when it contained information on task and process (Wisniewski et al., 2020) as it promoted deeper search for the causal reasons underlying the disequilibrium created from juxtaposition of conflicting explanatory frameworks. These results align with Hattie and Timplerley (2007) and Wisniewski et al. (2020) who argued that providing high-information feedback is a powerful instructional strategy. High-information feedback enables learners to understand their mistakes, the reasons for the formation of those mistakes, and the ways new scientific mental models can be attained, such as by replacement, differentiation, and coalescence (Carey, 1991).

This chapter contains the following sections. Section 5.1 interprets the major findings of the study. Each finding is discussed from quantitative and qualitative perspectives. Section 5.2 provides a brief summary of the participants' perspectives. Section 5.3 suggests theoretical implications. Section 5.4 draws implications for science education and learning designs. Section 5.5 outlines the limitations of the study, concludes the study, summarizes the main points of the discussed issues, and provides recommendations for expanding the tutor feedback model in future studies.

5.1. Findings and Discussion

This study investigated the following two research questions:

1) For learners with low prior knowledge of wave physics, what are the relative effects of NF, KRF, and EF on acquisition of concepts that are not prone to persistent misconception?

2) For learners with low prior knowledge of wave physics, what are the relative effects of NF, KRF, and EF on acquisition of concepts that are prone to persistent misconception?

The results revealed considerably greater knowledge gains in the EF condition compared to NF and KRF (Tables 4.10, 4.12) under specific circumstances. These differences were statistically detectable in the two cases of wave categories (Q3) and speed-medium association (Q4). These concepts, which were related to the robust misconception of entity-like behaviours of waves (Houle & Barnett, 2008; Hrepic et al., 2010; Pejuan et al., 2012; Wittmann et al., 1999), were well comprehended and correctly applied after elaborative feedback was provided by the tutor during the learners' inquiry process. This result was consistent with several other studies that found explanatory feedback results superior in inference making and learning improvement (Butler et al., 2013; Johnson & Priest, 2014; Moreno & Mayer, 2005).

The KRF treatment was not detectably different from the NF treatment with respect to the above concepts (Tables 4.10, 4.12). Prior research has produced mixed results regarding the effects of KRF on learning. Some meta-analyses indicate that knowledge of results feedback can be effective if it is not combined with self-related comments such as reward, praise, and punishment (Lysakowski & Walberg, 1982; Tenenbaum & Goldring, 1989). Some argue that it is mostly ineffective (Van der Kleij et al., 2012). And several studies have demonstrated that such feedback can be negatively correlated with both performance and learning strategies (Cutumisu, 2018) as labeling learners' answers as correct or incorrect can interfere with knowledge acquisition, reinforce fragmented explanations, and impede learning (Marsh et al., 2012).

Kluger and DeNisi (1996) argue that verification feedback benefits learning when compared to no-feedback conditions although many studies indicate that verification feedback is no more effective than receiving no feedback (Pashler et al., 2005). This study did not find any evidence that knowledge of results feedback was detrimental to learning. More research is required in this area as there are conflicting results in literature indicating that minimal feedback can both advance and hinder learning (Fyfe & Rittle-Johnson, 2016).

No statistically detectable differences were observed among EF, KRF, and NF regarding the frequency-wavelength relationship (Q1), amplitude-speed relationship (Q2), and the sound wave propagation principle (Q5). For Q1 (Table 4.7) and Q2 (Table 4.8), this was apparently because the EF treatment was not crucial to demonstrating knowledge of the concept on the posttest; and in the case of Q5 (Table 4.13), the EF treatment was apparently insufficient for demonstrating knowledge on the posttest.

5.1.1. How did Elaborative Feedback Influence Learning?

Feedback provided by an expert has long been considered as a crucial factor in enhancing content knowledge and learning skill acquisition (Azevedo & Bernard, 1995; Shute, 2008; Wisniewski et al., 2020). This study investigated whether tutor feedback assists learning and remediating misconceptions when learners are engaged in scientific inquiry within a simulation environment where diverse features and tools support inquiry and knowledge construction. The results indicated that despite the interactivity of the simulation and the real-time feedback it generated when variables were manipulated and observed, elaborative feedback given by a tutor strongly contributed to the learner rejecting ingrained non-scientific concepts and developing appropriate understanding in the case of two concepts. The information contained in the elaborative feedback (i.e., explanations, examples, analogies, and demonstrations) provided comprehensible, logical, confirmable, and relevant information which helped the learners create alternative explanations. The competing explanations generated disequilibrium which needed to be resolved. With tutor elaborative feedback, this conflict often led to corrective restructuring of the existing theoretical framework. This argument is based on the conceptual change theory of Posner et al. (1982), which considers dissatisfaction with the initial conceptual model as the first and most important element in the process of conceptual change. Dissatisfaction with prior conception must then be followed by exposure to a scientific conception that is intelligible, plausible, and fruitful (i.e., clear, sensible, and productive). Similar to Piaget’s notion of accommodation, this model views cognitive conflict as the main driver of radical restructuring (Carey & Spelke, 2008) as it challenges learners by starkly foregrounding the contradiction between inaccurate intuitive beliefs and accurate facts (Özdemir & Clark, 2007).

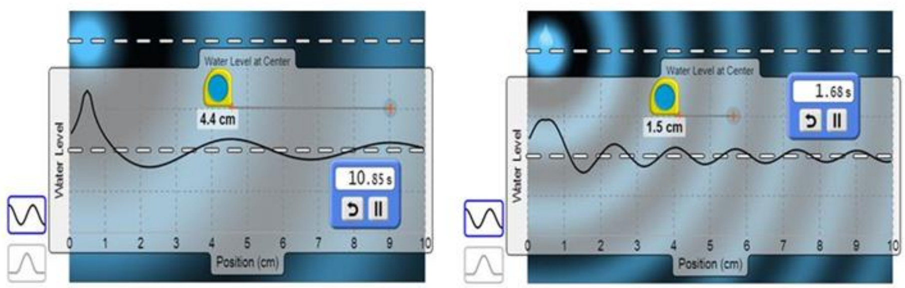
The following section discusses two types of outcomes: (a) when EF, relative to NF and KRF, did not detectably improve knowledge gain and (b) when it did. It will also elaborate on situations where knowledge gain was not statistically detectable across groups, but development of meaningful learning was observed by the researcher in learners’ explanations, statements, and questions as a result of elaborative feedback intervention. This observation-based analysis is meant to provide more information about the possible effects of elaborative feedback and devise research questions that can be investigated in future studies.

5.1.2. The Effect of Elaborative Feedback on Assimilation Learning

In the following sections, more details are provided about the learning behaviour of students while learning each concept.

Frequency-Wavelength Relationship (Q1). My subjective impression from observing participants' tests and explanations during the experiment was that adjusting the frequency value and measuring the wavelength using the implemented virtual ruler were adequate for learners to observe a relationship that was inversely correlational and predictive (Figure 5.1).

Figure 5.1 Frequency & Wavelength Relationship



Note. https://phet.colorado.edu/sims/html/wave-interference/latest/wave-interference_en.html

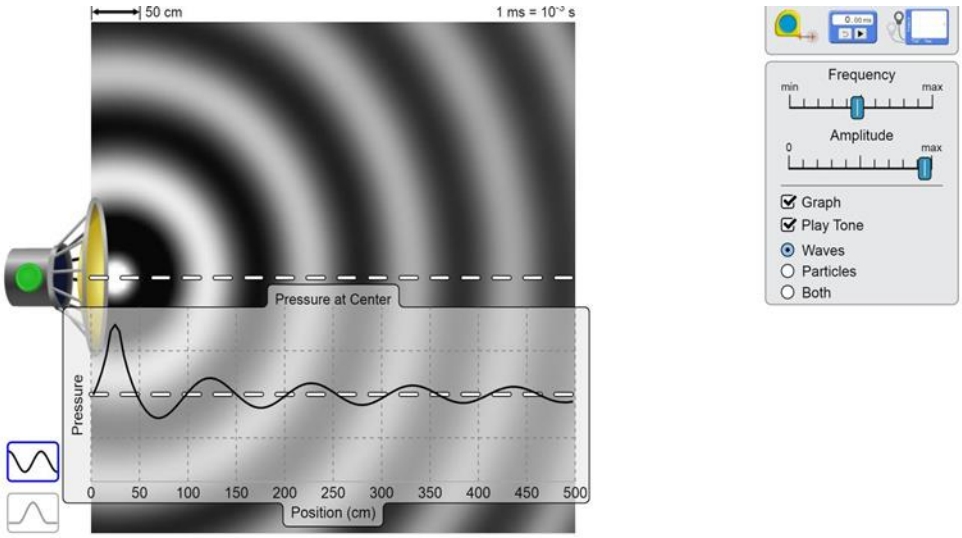
The NF participants who responded correctly to Q1 in the posttest (Tables 4.6 and 4.7) had discovered that frequency and wavelength were inversely related, and this relationship could be universally generalized to all types of waves. This discovery, which was confirmed by comparing detected patterns in light, sound, and water waves, was explained by such participants during the learning session with comments similar to the following example: “A wave with the highest frequency has the shortest wavelength and a wave with the lowest frequency has the longest wavelength. This relationship seems to be negative. That’s why when frequency doubles, the wavelength becomes half and vice versa.”

While the statistical analysis of posttest scores indicated that elaborative feedback did not lead to significantly greater knowledge gain in the EF group, EF seemed to lead participants to search for authentic scenarios for applying the newly acquired knowledge. For example, in response to the question of whether the inverse relationship of frequency-wavelength was relevant to understanding any real-life phenomenon, a participant stated: “Now that I know frequency is inversely related to wavelength, I’m thinking our brain waves probably have lower frequency when we’re relaxing or meditating. Because low frequency leads to longer wavelengths, which means more pauses or space between our thoughts.”

Elaborative feedback encouraged learners to explore the notion of frequency-wavelength beyond a mathematical demonstration based on manipulation of variables and measuring. Elaborative feedback acted as a stimulus that evoked the relevant schema from the memory and created a more complex interconnection between multiple pieces of information (e.g., frequency-wavelength, brain waves, relaxing mode, and racing thoughts). According to Shuell (1990), this interactive learning opportunity enhances mastery of knowledge, which is a precursor to meaningful learning, and promotes knowledge transfer to an authentic experience. This approach led to generalization of the learned principles as well as correction and refinement of prior implicit knowledge undetected by the pretest (Windschitl & Andre, 1998; Zhang et al., 2004).

Amplitude-Speed Relationship (Q2). By manipulating the amplitude of waves at various values (e.g., min, max, mid, and other points) and observing the corresponding speed of the wave in the simulation, learners investigated the relationship between amplitude and speed under various conditions. The Play Tone function of the simulation (Figure 5.2) allowed learners to listen to the tone produced at different amplitudes and discover that the amplitude of a wave does not affect the speed at which the wave travels.

Figure 5.2 Relationship between Amplitude and Speed of Sound



Note. https://phet.colorado.edu/sims/html/wave-interference/latest/wave-interference_en.html

Despite the fact that amplitude and speed are independent, this concept was counterintuitive for some learners. For them, the response to the prediction prompt was mostly “The higher the amplitude, the higher the speed of sound and vice versa.” This belief, which has been documented as a persistent misconception in other research studies (e.g., Pejuan et al., 2012), probably prevented many learners from developing an appropriate understanding of this relationship and its underlying reason. This misconception was evident in the explanations generated by several participants in the NF and KRF on the corresponding posttest question, in which they had to choose which slinky travelled faster (Figure 5.3).

On the other hand, the explanations provided in response to the above question by the EF group indicated that elaborative tutor feedback during the experiment was effective as it led to explanations such as “Change in amplitude causes change in the loudness of the sound but not the speed because when somebody speaks louder than another one, it would not mean faster. So, amplitude and speed don’t depend on each other” or “Amplitude does not change the speed of the wave. It would make it louder or quieter only. And this has nothing to do with speed.”

Although a difference in knowledge gain among the three groups was not statistically detected (p = .06, Table 4.8), the p-value was close to the conventional alpha level of .05. The effect size of the sample (V = .291) is also relevant. According to Cohen’s (1988) interpretation of effect sizes shown in Table 4.5, the sample had a medium size association between intervention and knowledge gain. I speculate that the effect of treatment would have been statistically detectable if the sample size were moderately larger and/or the measure of knowledge gain were more accurate.

Figure 5.3 Slinkies A and B are Attached to the wall and Pulsed at Different Amplitudes

Note. https://www.physicsclassroom.com/class/waves/Lesson-2/The-Speed-of-a-Wave

As argued by Bekkink et al. (2016), if new concepts are in conflict with pre-existing assumptions, students often prefer to keep the existing concepts and forget about the new ones. This is mainly because it is difficult to delete a mental model that seems coherent and logical and has been frequently employed. This approach to learning has been observed for other physics principles. For example, as they learn about classical mechanics, many learners do not understand why a moving object with constant velocity is in an equilibrium state (Halim et al., 2014). They often argue that any kind of motion is due to the imbalance of forces as they intuitively define equilibrium as being static.

In the EF condition, the tutor provided feedback by first reviewing the learner's initial response, possible reasons for the accuracy/inaccuracy of the response, and asking for alternative explanations of the phenomenon through questions such as “How do you explain your response? Can you give me an example? Do you see any variation in speed when amplitude changes? Does speaking louder also mean speaking faster and speaker softer mean slower?”

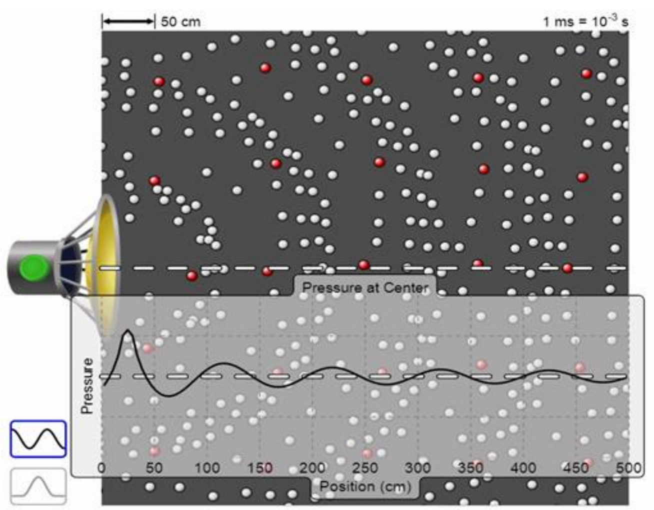
Change in learners’ understanding was evident in comments such as “I don’t know why I thought the height of the wave would make it more powerful and speedy. Knowing that the movement of the wave is the disturbance moving and not the water itself, makes it clearer. Greater amplitude makes greater intensity, which results in higher loudness. It makes sense!”

Students in the EF group appeared to be more active and engaged when they interacted with the tutor and responded to the content-related explanatory questions.

Many of them appeared to develop relational understanding, which required them to understand how and why amplitude and speed were not related. Similar articulation of understanding was not observed in the NF and KRF. In the latter groups, construction of knowledge and understanding was mostly demonstrated as extraction of rules from the detected patterns in the simulation. The identification of these patterns was mostly focused on how they were extracted and not the reasons explaining them. This type of understanding, which is referred to as instrumental thinking by Skemp (2006), seemed more evident in the comments made by the NF and KRF groups than the EF group.

Propagation of Sound Principle (Q5). Another concept with no statistically detectable differences in knowledge gain among the three conditions was sound propagation in the presence or absence of air. Participants manipulated frequency, amplitude, and wavelength of the waves generated by a speaker and observed the back-and-forth vibration of the air particles during sound propagation (Figure 5.4).

Figure 5.4 Propagation of Sound Waves & Particles



Note. https://phet.colorado.edu/sims/html/wave-interference/latest/wave-interference_en.html

Understanding this scientific phenomenon was examined through the following pre and posttest question: “What happens to the sound when (1) a solid, thick glass jar is put over it? and (2) when the air is pumped out from the jar?” The participants who responded to this question correctly provided explanations such as “If there is air in the jar, the sound can still be heard - might be slightly quieter though. But if the air is pumped out of the jar, the sound would be almost gone as there is no medium to travel through" or “The jar creates a muffling effect like a barrier and therefore the sound would be quieter. But if the air is completely pumped out, the sound can't be heard. It'd be completely silent." These explanations indicated that understanding the principle of energy transfer through vibration of the particles of the medium through which the sound traveled was aligned with some learner's prior knowledge and experiences. The analysis of responses to the pre- and posttests revealed that learners' existing experiences had influenced their rationalization and conception of the sound propagation principle. For example, several participants described the above situation as hearing a ringing cell phone hidden in a pocket versus a ringing phone on a table. This pairing phenomenon is common in science education. If a new concept is aligned with the learner's prior knowledge and the prior knowledge is accurate, learning occurs with understanding and coherence. As learners' decision criteria for solving related problems are often based on the evidence that has been accumulated over time (Crooks & Alibali, 2013) and confirmed by linked experiences.

For Q5 (Table 4.13), gain was low across all groups including the EF group. Potential reasons for this outcome could be existing misconceptions that were deeply entrenched with respect to sound waves propagation (Hrepic et al., 2010; Pejuan et al., 2012; Wittman et al., 1999) along with erroneous understanding caused by insufficient information presented by the simulation for this concept (e.g., the speed of sound in a vacuum is zero meters per second). This argument does not necessarily make elaborative feedback redundant. Sometimes the additional explanations provided in elaborative feedback may be needed to provide an opportunity for in-depth analysis of the learned concepts, profound questioning, and flexible implementation of the new principles in various contexts. This type of approach was observed in the EF group when they asked questions such as: "Can sound be heard in space?" "What is the effect of air pressure on the intensity of sound?" "What happens if the bell jar is moved to the moon?" and "What would be the effect of gravity on the sound wave?"

Further research is required to determine what instructional guidance supports learning of this concept.

5.1.3. Elaborative Feedback Enabled Conceptual Change

This section discusses the role of elaborative feedback in learning wave category membership and medium-speed relationship in sound waves.

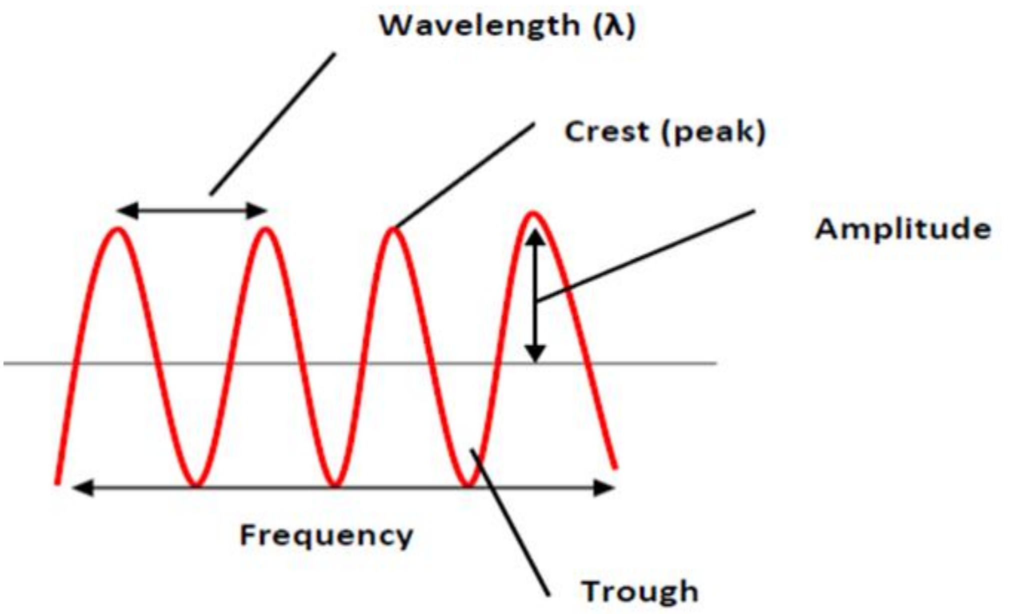
Wave Category Membership (Q3). There were three types of waves in the simulation, one produced by a dripping faucet, one produced by an audio speaker, and the other one by a laser pointer (Figure 5.5).

Figure 5.5 Different Sources for Producing Waves in the Simulation

Note. https://phet.colorado.edu/sims/html/waves-intro/latest/waves-intro_en.html

The graphs produced by these devices indicated similar structures and common features such as crests, troughs, amplitude, frequency, period, wavelength, and speed (Figure 5.6).

Figure 5.6 A Snapshot of the Wave at Any Given Time



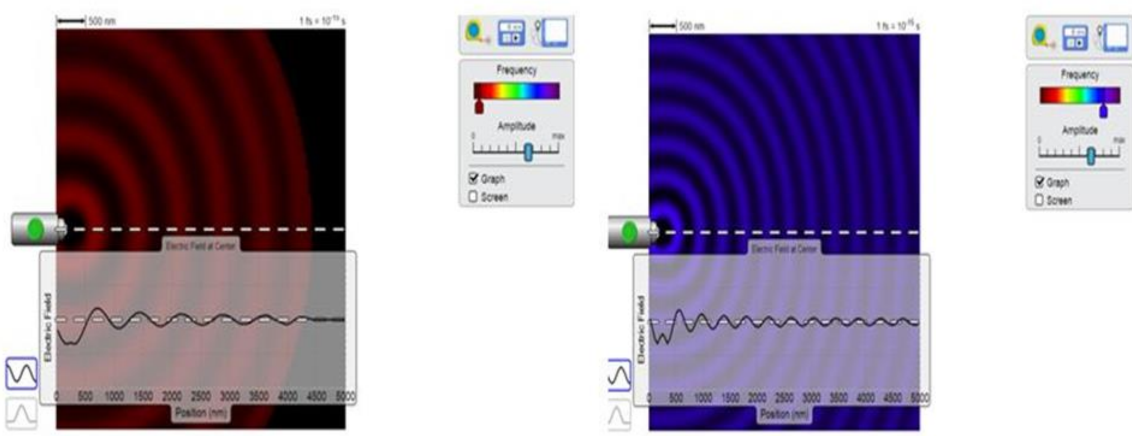
Note. https://sciencerifi.co.uk/Content%20pages/Physics/Waves.html

While these features were explicitly evident in the simulation, there were distinguishing features that needed to be discovered and described by the participants.

For example, light did not need a medium to travel through, while sound and water required a medium to transport energy from one location to another.

When participants were prompted to predict and explain how waves resembled and differed, they mostly explained as follows: “Waves are all similar because they all go up and down like the ocean waves or waves of audio clips”, “Waves have different colors and speeds, but they all look the same” and “Light is super-fast but water and sound are much slower. That’s why lightning can be seen before thunder can be heard.” To support their explanations, most participants referred to the demonstrated waves in the simulation and provided explanations such as “See? All waves are cyclic. They go up and down. They have length and height. They can go faster or slower depending on their frequency and environment.” Some learners also noticed several differences such as the gradual change of color from red to violet in different frequencies of light and described their observations as “Different frequencies of light have different colors. Higher frequencies appear to be blue or violet, shorter frequencies appear to be red or orange, and green in somewhere between. Light seems to be different from sound and water.” Or “Water waves are created as energy is passing through water and circular motion is generated. Same thing happens in sound. But I’m not sure about light. I guess it’s the same.”

Figure 5.7 Frequency & Colour in Light Waves



Note. https://phet.colorado.edu/sims/html/wave-interference/latest/wave-interference_en.html

Learners observed water waves using water for the medium, sound waves using air particles, and light waves traveling in some black space. To ensure that the black background in the simulation was equated with vacuum completely absent of particles, the researcher advised participants to interpret the black screen as no air and no particles. They were informed about this condition at the beginning of the session and before performing the corresponding task. However, the feature of the necessity of a medium was not considered as a fundamental differentiating factor between the waves by most participants. It seemed that prompting learners to observe and explain had no detectable effect on accurate categorization of waves into the ones with medium and the ones with no medium for travel - mechanical and electromagnetic types - unless elaborative feedback was provided by the tutor.

Although the NF participants noticed a few differences among the three types of waves, they typically failed to classify them into the two major categories of requiring and not requiring a medium to travel. Instead, they assigned all waves to the most general ontological category of waves and ignored the distinctive factors leading to further essential classifications. This overgeneralization is common in novices and has been repeatedly observed in previous studies (e.g., Eshach et al., 2018; Hrepic et al., 2010; Leccia et al., 2015; Pejuan et al., 2012; Wittmann, 2003).

The common misconception of entity-like behaviour of waves – movement of matter from a start point to an end point of a medium – is in fact a preconceived notion deeply entrenched in daily life experiences. By adopting this view, many individuals think that all waves behave like an individual object or entity. Similar misconception has repeatedly been observed with regard to other concepts such as heat and cold as well as heat and temperature (Alwan, 2011; Kesidou & Duit,1993). Many students become confused about the concepts of heat and temperature in physics as they think these two concepts belong to the same category and can be used interchangeably.

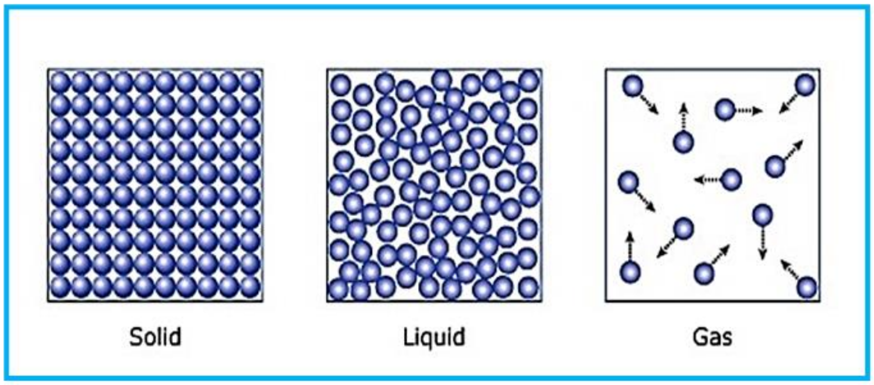
Students' inaccurate and incomplete knowledge of scientific concepts creates a rigid system of thinking that interferes with meaningful learning (Choi & Hannafin, 1995). I argue this alternative understanding can be transformed and aligned to justified scientific theories if expert/tutor elaborative feedback is provided. Since incorrect reasoning is the source of incorrect understanding and explanation, one of the ways to reduce or change this approach is by providing accurate explicit reasoning that is plausible and satisfactory for the learner and prompts them to clarify (further explain, rephrase, illustrate, or demonstrate), attend to selective evidence (seek substantiation for their claims), evaluate (speculate beyond the collected data), and extend knowledge based on the collected data (Gooding & Metz, 2008).

The results of this study indicated that, in the EF group, the misconception of entity-like behaviour of waves (or matter transfer) was recognized as an inefficient model of thinking which needed to be replaced with a more developed conceptual model that could explain the encountered phenomenon of wave traveling. This new model – referred to as energy transfer – was developed after the tutor provided detailed information about transmission of different types of waves. The detailed explanatory information provided by the tutor bridged the gap between the learner's incomplete existing knowledge and the intended knowledge. Elaborative feedback provided what learners lacked by presenting (1) correct detailed information of the two categories of waves (2) examples drawn from common experience and (3) asking confirmatory questions. For example, the tutor initially explained "Sound waves cannot travel in the vacuum of space because there is no medium to pass through. However, light can travel in space in areas where there is no matter." This information was then followed by confirmatory questions, such as "Do you think your friend and you would be able to verbally communicate in space?" to which participants responded, "No, because there is no air to transfer the energy. Sound needs to vibrate molecules to travel."

Research shows learners who lack appropriate prior knowledge often achieve better learning and greater understanding if elaborative feedback is provided during the process of knowledge construction (Moreno, 2004). Feedback allows learners to select, organize, and integrate knowledge and construct meaningful understanding of the new concepts using the available resources such as the tools and techniques in the simulation. Feedback can therefore lead to substantial derivation of new knowledge and the retention of that knowledge (Butler et al., 2008).

Medium-Speed Relation (Q4). After reviewing the molecular structure of different types of matter based on the illustration provided in the handout (Figure 5.8), participants were prompted to predict the relationship between speed of sound in air versus that in water.

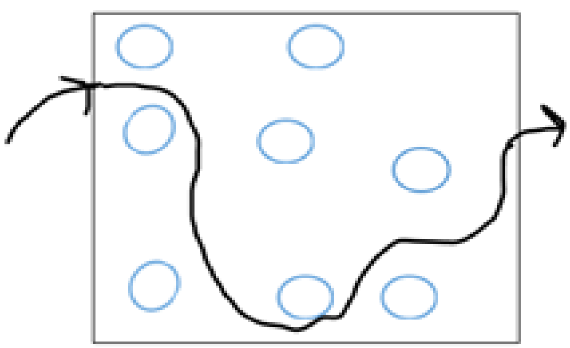
Figure 5.8 States of Matter



Note. www.sciencelearn.org.nz

Student responses to the prediction prompt indicated that nearly all explanations were based on the traffic flow principle - the looser the molecules of matter, the faster the speed of sound and vice versa. This prediction, which was inaccurate, was justified by drawing a picture similar to Figure 5.9 and providing explanations such as: “The speed of sound is faster in gases and slower in liquids because it’s easier for sound waves to go through the gaps between the gas particles.” Or “The speed of sound is faster in air compared to that in water because air molecules are spread apart and move freely by each other. You know, it’s like walking in a crowded versus non-crowded subway station. Of course, it’s much easier and faster to walk though when less people are around.”

Figure 5.9 Movement of a Sound Wave through Gas Molecules Sketched by a Participant



As stated earlier, this object-based (or entity-based) reasoning has repeatedly been observed and reported by other physics education researchers in the past (e.g., Eshach et al., 2018; Hrepic et al., 2010; Leccia et al., 2015; Pejuan et al., 2012; Wittmann, 2003). Most novices tend to think that sound is a substance-like entity transported by the particles of the medium, which moves from one place to another.

Following the prediction prompt, participants read the facts about the speed of sound waves in air (343 m/s at room temperature) versus that in water (ranges from 1450 to 1498 m/s). Subsequently, they were prompted to explain (i) whether their prediction was aligned with the given facts and (ii) whether they could explain the reasons for their prediction. In response to these prompts, participants provided explanations such as, "Oh! Very interesting! I never knew the speed of sound was actually higher in water than in air. Based on the state of matter picture, it's probably because water particles are more squeezed together so the molecules can collide more and transfer sound waves faster, something like a tight spring." Or "Wow! Not easy to imagine. The reason must be related to the space between the molecules. It seems density makes a difference in the speed of sound. The denser the material, the faster the speed of sound." The provided explanations were all accurate and exhibited similar logical consistency, regardless of the condition of the participants.

It may appear that prompting learners to predict based on existing knowledge and explain based on given scientific facts were sufficient for them to discover the relationship between speed and density as all participants managed to accurately deduce such relationships in air and water. However, the performance of the participants on the posttest indicated that only the EF group managed to transfer their discovered knowledge to solids and predict the speed of sound in a new context by extrapolation (See Tables 4.11 and 4.12 in Results Section) and gain a significantly higher knowledge gain on medium-speed relationship (Q4).

Considering all groups succeeded in generating correct explanations for the speed of sound based on properties of gases and liquids, why did only the EF condition manage to generalize the newly discovered principle of the tighter the molecules, the faster the speed of sound to solids?

The explanations provided by the NF and KRF groups on the posttest indicated the persistence of entity-like behaviour misconception and its interference with correct generalization of the principle of the tighter, the faster in the next context. When the participants in the above groups were asked to explain why they did not generalize the previously deduced principle of medium-speed relation to solids, they said that “The speed of sound is faster in liquids because the molecules are denser than in gases. But there is no way that the speed of sound can be faster in solids compared to that in liquids and gases because sound waves cannot travel through the space between solid particles. So, I would say, the speed of sound is the fastest in water.” Or “You know, in air and water the molecules can move around relative to each other but not in solids" and “I just learned the speed of sound is higher in liquids than in gases but I’m not sure about liquids versus solids. It seems that solids are too rigid to let any wave travel through. I don’t think sound waves can move freely among the molecules. I think I should go with the option of liquids for this question.”

As noticed in several participants’ explanations, those who did not receive detailed explanations and supportive examples through tutor elaborative feedback kept their misconception of entity-like behaviour of waves despite being exposed to a similar situation earlier in the experiment and generating correct explanations based on the given scientific facts. The very same misconception persisted and was employed in a new context shortly after. This observation implies that self-explanation alone and self-explanation along with knowledge of results feedback were insufficient for generalizing the previously self-discovered rule of medium-speed and eliminating the misconception of object-like behaviour of waves. Elaborative feedback was imperative for accurate understanding of medium-speed relation and eliminating the misconception.

The posttest performance of participants indicated misconceptions continued to exist unless elaborative feedback was provided to address the underlying structure of previously held information and a new model was developed (Pridemore & Klein, 1991).

Elaborative feedback confirmed students’ correct understanding, expanded their knowledge, and allowed them to encounter their previously held fragmented knowledge and incorrect presuppositions. This confrontation created the discomfort of disequilibrium, which was an essential catalyst to shifting learner understanding of the old concept of wave entity behaviour and resolving the generated conflict. It also made them realize that entrenched misconceptions could be challenging to overcome as they often appear to be reasonable and applicable to various experiences (Gorsky & Finegold, 1994; Vosniadou, 2008). This cognitive push-and-pull struggle between the old and new concept was observed when explanations such as the following was provided by the tutor: “Sound waves are transported from one location to another by means of particle-to-particle interaction. When sound waves are moving through a medium, as one air particle is displaced from its original position, it exerts a push or pull to its nearest neighbors, causing them to be displaced from their rest position. This particle interaction continues throughout the entire medium, with each particle interacting and causing a disturbance of its nearest neighbors.” This tutor explanation gave rise to logical inferences such as “Oh, the motion of molecules is like shaking back and forth to transfer energy. Nothing must go through the gaps between molecules. So, it’s possible that sound travels faster through a solid than a liquid, and faster through a liquid than a gas.”

Interestingly, many learners stated that the concept of the medium-speed relation was difficult to grasp since their general experience with sound was the opposite. For example, they said “It’s hard to imagine that waves don’t actually move around. You know, when you see the ocean waves, it feels like the waves move all the way from the middle of the ocean to the shore!” or “To be honest, it was confusing at the beginning. But it makes sense when you think about sound as a disturbance that is propagated through the collisions between the particles. In that case, one molecule hits the neighbouring molecule, and the next one bumps into the next and so on. So, the closer the molecules the faster the speed of sound.”

5.1.4. Interpretation

Research on inquiry learning indicates that learners can benefit from guidance to overcome several challenges such as analyzing data and making inferences (Alfieri et al., 2011) as well as critically assessing, explaining, rule generating, and applying newly learned principles to authentic contexts (Hajian et al., 2021). In this study, the three conditions of NF, KRF, and EF received guidance from various resources such as an information handout, pre-designed structured tasks with embedded prompts, and the simulation itself. These informational resources were supplemented with additional support from the tutor in the form of feedback for two groups: one with knowledge of results and the other with elaboration.

The results revealed that elaborative feedback was a factor for improved learning when participants' prior knowledge was incomplete, fragmented, and faulty and could not be completed and corrected by utilizing the provided resources. In such cases, the tutor's elaborative feedback acted as a correcting and enriching agent. If learners did not carry deeply held counter-intuitive misconceptions interfering with their learning process, elaborative feedback did not make statistically detectable differences among the knowledge gain of the groups. However, it did appear to be effective for deeper relational understanding and creating connections between produced hypotheses and gathered evidence. This effect was evident through the explanations produced and follow up questions asked by the participants in the EF group. According to Skemp (2006), there are two types of learning. One is the result of observing patterns among data, generating rules and formulas and the other is about understanding the underlying reasons such as why and how a specific concept or principle connects and maps to similar knowledge and experiences. The latter was mostly observed when EF was used as an intervening instructional support.

Elaborative feedback allows learners to confront their existing assumptions and evaluate the applicability of those assumptions in authentic contexts. Observing the participants' learning process and analyzing their pre-post scores indicated that by receiving feedback through tutor-learner interaction, learners often realized why they were correct or incorrect, whether their alternative ideas/theories made sense, whether their revised assumptions functioned appropriately, and whether their generated cognitive conflicts had been resolved.

Conceptual change requires multiple coordinated changes in cases when flawed mental models appear to be coherent and logical. In such conditions, by merely exposing learners to rich multimedia/instructional environments, learning does not result in deep comprehension, understanding, and transfer (Kozma, 1994). The processes of selecting, organizing, translating, coordinating, and integrating information across modalities and formats must be supported for learning to occur (Ainsworth, 1999).

Posner et al. (1982) argue that a new concept can be accommodated when some level of uneasiness and conflict is created between the new and old model of thinking. If the new concept is intelligible and plausible as well as applicable to various conditions and situations, the new concept emerges as another reasonable option for explaining the intended learning phenomenon and a cognitive competition occurs between the existing novice and new expert model (Strike & Posner, 1985). This competition is highly significant for the process of conceptual change as it prompts learners to compare the validity of the competing ideas using the provided tools in the simulation, select the idea or model that is reasonable, and eliminate the ideas that fail to fully explain the new phenomena. For example, when elaborative feedback about wave movement was provided, learners realized that ocean waves do not carry the water molecules from one position to another. Rather the wave's energy travels through the water, leaving the water molecules in place, similar to a bug moving up and down on top of ripples in water without moving forward (Figure 5.10, National Aeronautics and Space Administration, 2010). The use of analogy for clarifying the scientific explanation of wave movement was highly effective for remediating the existing approach as this approach was based on the common misconception of transportation of matter and not energy. This contrast allowed them to experience a need to reduce the generated dissonance by restructuring and modifying the existing schema (Gorsky & Finegold, 1994). This active engagement in a deliberate and meaningful belief revision was found to be highly productive in belief revision and, therefore, fundamental for conceptual change (Vosniadou et al., 2001).

Figure 5.10 Water Waves Transfer Energy Not Matter

Note. https://science.nasa.gov/ems/02_anatomy

The detailed information about sound wave movement made the EF participants realize their initial misunderstanding had originated from object-like thinking about waves. According to many researchers, students misrepresent certain concepts as a kind of entity rather than a kind of process (Chi, 2005; Chi & Hausmann, 2003; Eshach et al., 2018). For example, many learners think heat is an object that carries heat and can move from a place to another, or it is a sweater or mitten that actually produces heat.

By knowing the incorrectness of the existing assumption, learners consciously and selectively attended to the feedback information. The feedback explanation allowed them to confront their misconception and reject prior beliefs by stating "Oh, so sound waves do not travel like individuals. I mean the more crowded does not mean slower travel. Sound waves travel through the particles by causing them to vibrate back and forth, right?" to which the tutor responded "Yes, it's correct! When a sound wave is moving through air, as one air particle is displaced from its rest position, it exerts a push or pull on its nearest neighbors, causing them to be displaced from their equilibrium/rest position. This particle interaction continues throughout the entire medium, with each particle interacting and causing a disturbance of its nearest neighbors." This explanation was often followed by comments such as "This concept is hard to believe since our general experiences lead us to hear reduced or garbled sounds in water or behind a door," which indicated learners' deep engagement with the nature of the new theory and acknowledgement of the counter intuitiveness of the concept.

The reasoning processes explained in the elaborative feedback provided learners with the information and examples that they needed for conceptual generalizations (Mata-Pereira & da Ponte, 2017).The majority of NF and KRF participants could not generalize the medium-speed relationship to solids and failed to differentiate light as an electromagnetic wave from sound and water as mechanical waves although these relationships were easily discovered by comparing the molecular structures of air and water by all participants and the differences among the waves were visible to them. The discovered principles remained limited to only specific contexts and could not be transferred to other contexts.

Elaborative feedback was necessary for refining and expanding an already discovered principle in alternative conditions. As noted, in the absence of elaborative feedback, the original misconception was still integrated into the new model of thinking. This is highly consistent with previous studies indicating novice students, with insufficient prior knowledge or partially incorrect knowledge, learn more from studying examples and instructions than from solving a problem (or interpreting a new phenomenon) requiring predicting and hypothesizing (Cooper et al., 2001; Leppink et al., 2012; Mayer & Johnson, 2010).

As research shows, engaging in explanation assists with the discovery of generalizations underlying the explained phenomena (Williams & Lombrozo, 2010). Why was explanation adequate for generalizing the acquired rules and relations of the concepts of frequency-amplitude and amplitude-speed and not for the concepts of waves categorization and speed-medium relation in sound?

I argue that generating explanations for oneself to analyze and understand new information is often an effective learning strategy as it allows learners to make inferences beyond the provided information (Bisra et al., 2018; Chi et al., 1994; Rittle-Johnson & Loehr, 2017) and facilitates knowledge integration and cognitive conflict resolution (Chi, 2000). However, self-explanation can repair and enrich existing knowledge if the learner, with incomplete knowledge, has access to accurate information or improved knowledge structure. If the learner's knowledge is incoherent or incorrect, generating explanations may strengthen the misconception and faulty assumptions instead. According to Chi et al. (1989), one needs to have a complete understanding of underlying theoretical assumptions of a domain theory to be able to construct high quality accurate explanations. Students can learn with understanding if they can overcome the incompleteness of an example or an observed phenomenon by making inferences from the presented information and then applying the general inferences to non-isomorphic problems or situations with different conditions (Hajian, 2019).

According to Posner et al.'s theory of conceptual change(1982), which for decades has been a leading model of learning in science education, the following four conditions need to be met before any conceptual shift can occur: (1) feeling dissatisfaction with the adequacy of the previous knowledge and experience in explaining new encountered phenomena; (2) receiving a new conception that is clear, logical, and intelligible; (3) realizing that the new conception, idea, or theory is plausible and persuasive; and (4) understanding that the new concept or theory is fruitful and productive in resolving the existing conflict. In this approach, a learner is seen as a scientist and the process of learning, similar to any other scientific investigation process, follows several steps such as observing, testing, collecting data, finding patterns, and generating rules (Hajian et al., 2021; Pedaste et al., 2015). Therefore, confronting a cognitive conflict and resolving it are core elements of conceptual change.

In this study, the embedded self-explanation prompts (prediction and justification) were meant to help learners activate their prior knowledge, assess the validity of this knowledge, and use it for analyzing, interpreting, and explaining the new information obtained from the assigned inquiry activities conducted in the simulation. On the other hand, the elaborative feedback was intended to be intelligible, plausible, and fruitful to support learners in resolving their cognitive conflicts which were assumed to be created by the discrepancy between the predicted explanations of phenomena and the observations of the simulated phenomena.

The results indicated that employing these two instructional tools strongly supported learners' conceptual change in the two areas of medium-speed and wave categorization.

While the outcomes of this study indicated strong treatment effects, the interpretation I have presented to this point is somewhat simplified and does not capture the more complex picture drawn by current research in conceptual change. Although in traditional conceptual change literature replacement of alternative conceptions with scientific conceptions constitutes the definition of change, we cannot simply remove the learner's faulty notion and replace it with a correct one (Özdemir & Clark, 2007; Vosniadou, 2008). Many current researchers define conceptual change with regard to competition of responses at a deeper cognitive level (Asterhan & Dotan, 2018). This response competition scheme is supported by recent evidence showing that conceptual change involves both an improved capability to construct the correct scientific explanation, as well as inhibition of automatically activated, but irrelevant schemas (Shtulman & Valcarcel, 2012; Potvin et al., 2014).

Understanding the cognitive and metacognitive mechanisms involved in the process of understanding feedback is quite complex. We do not know what latent factors at any given moment select and activate the cognitive processes that restructure cognition (Herd et al., 2013).

The principles of the classical conceptual change approach described above have been challenged by other theories over the years. For example, according to the situated learning perspective conceptual change cannot be construed as an entirely individual process that takes place internally. Learning is also a co-constructive activity that occurs through interaction with external entities such as the tutor, peers, and environments (Lave & Wenger, 1991). Similarly, motivation theorists argue that conceptual change is not simply cognitive processing of information independent of affective involvement (i.e., “cold cognition”) (Pintrich et al., 1993; Vosniadou, 2007). A positive tutor-learner relationship can be highly encouraging and motivating for learning (Amadi & Paul, 2017). In fact, in the interviews conducted at the end of the experiment, many EF participants stated that receiving detailed information about the task performance, the suggested modifications, and exchanging ideas with the tutor were highly encouraging to them. Interestingly, most participants in the NF and KRF groups spontaneously proposed that elaborative feedback would be a great help in enhancing their understanding of the material and improving their learning.

Another argument to consider regarding this phenomenon is that feedback over a long period of time may inhibit learners’ effort to explain what they observe. Too much feedback may lead to less cognitive effort to develop informal hypotheses (Hattie & Timperley, 2007), justifications, and explanations, even though detailed explanation provided by an expert more generally results in lower extraneous cognitive load, higher germane cognitive load, and enhanced motivation (Wang et al., 2019).

5.2. The Participants’ Perspectives

Students’ responses to some of the interview questions indicated that prompting them to initially conduct inquiry activities about various components of light, sound, and water waves helped them extract their prior knowledge and generate rational inferences. According to most participants, they felt cognitively ambivalent if they were provided with only correct/incorrect responses. They often expected to receive additional information for deeper investigation and inquiry.

Several participants mentioned it was nice to receive feedback after working hard towards a challenging task. Some others said it was interesting to find out the reason behind the false thoughts. They explained their approach using statements such as, “When you receive feedback on your wrong responses and understand the underlying logic of an occurrence, it feels like you’re actually learning something.” One student said

“After receiving detailed explanations, everything made sense. It’s like all the pieces of the puzzle came together and everything became clear.” and another mentioned, “I feel like I’ll always remember what I learned today. The stuff I learned today is not disconnected anymore.”

5.3. Theoretical Implications

The results of this research point to the type of tutorial guidance needed to promote learners reorganizing their conceptual knowledge while learning physics within an interactive simulation environment.

Similar to Vosniadou (2008) and Chi et al. (2012), the theoretical position of this study assumes the knowledge system of novices does not simply consist of isolated patterns, rules, and principles. To the contrary, the learner's naive theoretical system is a highly coherent and consistent theory that has frequently been confirmed by their everyday life experiences (e.g., entity-like behaviour of objects such as easier movement of a ball in less versus more crowded areas).

The task of changing any firmly established belief is challenging but can be facilitated by tutorial prompts to explain and then elaborative tutorial feedback, in response to the learner’s explanation. The design and implementation of elaborative feedback can be complex as it is often based on prior diagnosis of learner knowledge, the complexity of the tasks that intentionally target the expected misconceptions, and the learning environment.

5.4. Implications

The findings of this study provided evidence that self-explanation and elaborative feedback can support activation and refutation of scientific misconceptions under certain circumstances. Whether misconceptions originate from conceptual misunderstanding, non-scientific beliefs, or preconceived ideas, prompting learners to think about causal relations among the observed phenomena and explain them can help learners activate their prior knowledge. It also allows tutors to improve their support for learners by identifying and correcting their faulty mental models.

The results have practical implications for instructional designers and educators. For example, they can be beneficial in identifying learners' existing knowledge gaps and cognitive structures. Identifying the learners' cognitive structures can effectively help educators to identify knowledge gaps, select appropriate material, and relate new materials to existing knowledge (Ifenthaler et al., 2011).

Any tutor-delivered guidance in inquiry learning environments can be improved if learners are first challenged to respond to self-explanatory questions, such as prediction and justification prompts, then supplied with informative, detailed, and elaborative feedback. The pedagogical community can deploy this intervention in real and virtual environments to improve student-centered learning and autonomous knowledge acquisition in active learning environments. In the near future, it will likely be possible to implement this intervention via an automated pedagogical agent capable of detecting the learner's actions in the simulation and recognizing the learner's utterance to provide appropriate feedback when required.

It is worth mentioning that no one single tool functions as a "silver bullet" to resolve all learning challenges. This study added another pedagogical tool in the science educators' toolbox. This tool might be of high value for those who seek practical solutions for science learners in similar settings with similar challenges.

5.5. Limitations and Recommendations

The findings of this study are limited to undergraduate recruits learning wave physics using a simulation as studied in a controlled laboratory setting. To increase the generalizability of the results we require additional research in other curricular domains with different types of simulations using a range of research methodologies.

Improving students' long term knowledge retention and transfer of learning is the primary goal. Since this experiment was limited to one session, delayed retention and transfer were not investigated. Deploying a research design similar but extending for multiple sessions would address this shortcoming.

At the end of the study, many participants stated that elaborative feedback was not only highly beneficial in comprehending new information, but it was also encouraging, engaging, and motivating. Considering engagement and motivation can greatly enhance learning and achievement, assessing and measuring these factors may shed more light on the integrative role of self-explanation and feedback in simulation-based inquiry learning.

Last but not least, individual differences can lead to substantial differences in learning achievement and outcomes (Bielaczyc et al., 1995). Individual differences in working memory capacity can affect how feedback is processed and how different types of feedback can increase learning (Fyfe et al., 2015). Considering these internal factors in relation to the instructional interventions in further research may assist us in customizing instructional guidance and creating flexible learning options for students.

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Appendix A.

Task Content

Task A. The purpose of Task A is to investigate how changing amplitude and frequency affects the shape, size, and intensity of water waves.

Now open the Wave Interference PhET simulation. Start with one drop**.** Increase and decrease the **frequency** and **amplitude** setting (try three different settings of **min, average, and max**) and answer the following questions.

I. Describe your observations and explain your conclusion. For e.g., if you notice that the blue color of the ripples becomes brighter and more intense, try to find a pattern/rule. First **predict** the answer to the following questions. Then, investigate using the simulation, and **explain.**

II. What happens to the water waves when amplitude changes? What happens to the water waves when frequency changes? **Explain.**

III. What happens to the intensity of the color of the water waves when amplitude changes? **Explain.**

IV. Do you think the same relationships hold in light, water, and sound waves? In what aspects light, sound, and water waves are different? **Justify your explanation**.

Task B. The purpose of task B is to find the relationship between frequency & wavelength in waves.

I. Based on the definition of **Frequency** and **Wavelength**, what do you **predict** about their relationship? Do you think this relationship is direct or inverse?

II. Now please go to the simulation and investigate this relationship in all three waves (light, sound, and water). Is there any relationship between **Frequency** & **Wavelength? Justify your Explanation.**

Task C. The purpose of task C is to investigate the relationship between frequency, amplitude, wavelength, and speed of the wave.

I. What factors do you think affect the **speed** of sound waves and why? **Explain.**

II. Now test your predictions using the provided wave applet. Were you right or wrong? **Justify your explanation.**

Task D. The purpose of task D is to try to figure out why the speed of sound is different in various media.

I. What do you think about the speed of sound in the following mediums, air versus water? In which medium the speed of sound is faster? **Explain your prediction.**

II. The speed of sound varies greatly depending upon the medium it is traveling through. For example, the speed of sound is much faster in liquids than in gases. The speed of sound in air is approximately 343 m/s at normal room temperature while the speed of sound in water ranges from 1450 to 1498 meters per second. Considering the different structures of liquids and gases in the handout, how do you **explain** this difference? **Justify your explanation.**

Appendix B

Pretest and Posttest

1. A cat can hear sound frequencies up to 70,000 Hz. Bats send and receive ultrahigh frequency squeaks up to 120,00Hz. Which one of them can hear shorter wavelengths, cats or bats?

A. Eventually they hear the same wavelength to locate their prey

B. Bats can hear sound of shorter wavelength

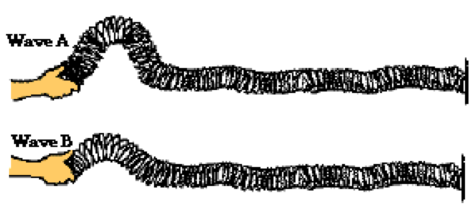
C. Cats can hear sound of shorter wavelength

D. Only ocean animals such as dolphins can create short wavelength sounds as they need to communicate in water

E. None of the above

Explain why: ---

2. A teacher attaches a slinky to the wall and begins introducing pulses with different amplitudes. Which of the two pulses (A or B) below will travel from the hand to the wall in the least amount of time?



A. Slinky A with higher amplitude

B. Slinky B with lower amplitude

C. Both at the same time

D. Amplitude only applies to sound waves

E. There is not enough information

Explain why: ---

3. What is the major difference between sound, water, and light waves?

A. All waves are the same as they have same properties

B. Sound and water waves form ripples but light waves do not

C. Light waves are different because they do not need any medium to travel

D. Sound waves are everywhere but light waves do not exist everywhere

E. None of the above

Explain why: ---

4. Which of the following statements is true?

A. High frequency sound travels faster than low frequency sound

B. High amplitude sound travels faster than low amplitude sound

C. Speed of sound changes when amplitude, frequency, and wavelength all change at different times

D. Sound waves travel the fastest in water

E. Sound waves travel the slowest through gases and fastest through solids

Explain why: ---

5. A speaker is playing a constant note. What happens to the sound when you (1) put a solid, thick glass jar over it and (2) pump the air out from the jar? Picture was provided.

A. There would be (1) hardly any difference and (2) hardly any difference as sound waves travels through both mediums

B. There would be (1) hardly any difference and (2) much quieter due to air resistance in the second case

C. There would be (1) noticeably quieter as the jar is solid and denser and (2) much louder due to lack of air resistance

D. It would be (1) noticeably quieter and (2) near silence

E. None of the above cases

Explain why: ---

Appendix C

Information Handout

Wave Properties

Light, sound and water all travel as waves

Wave: a wave is a **disturbance that transfers** energy from one place to another. Waves can **transfer** energy over distance without moving matter the entire distance.

A. **Frequency (f):** the number of cycles in a second. The **hertz** (symbol: **Hz**) is the derived unit of **frequency** in the International System of Units (SI) and is defined as one cycle per second.

B. **Amplitude (A):** the amplitude measures the height of the crest of the wave from the mid line. The amount of energy carried by a **wave** is related **to** the **amplitude of the**

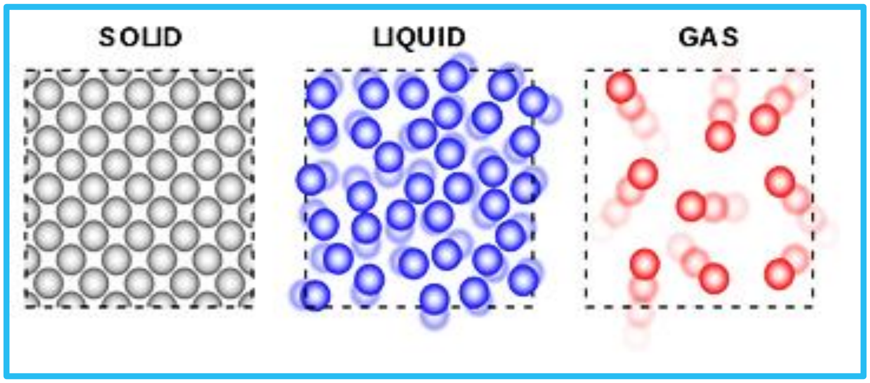
C. **Period (P):** the time it takes from one peak to the other (to complete a cycle) is the **period**.

D. **Wavelength (λ):** a wavelength is a measure of distance between two identical peaks "Crest" (high points) or "Troughs" (low points) in a wave. **Wavelength** is measured in meters (m) - it is a length after all. The upside-down y is lambda, which stands for wavelength.

E. **Speed (S):** wave speed is the speed at which a wave travel. Sound waves travel through a medium.

Three States of Matter

In solids, the particles are tightly packed together. In liquids, the particles have more movement, and in gases the particles are spread out and in continual motion.



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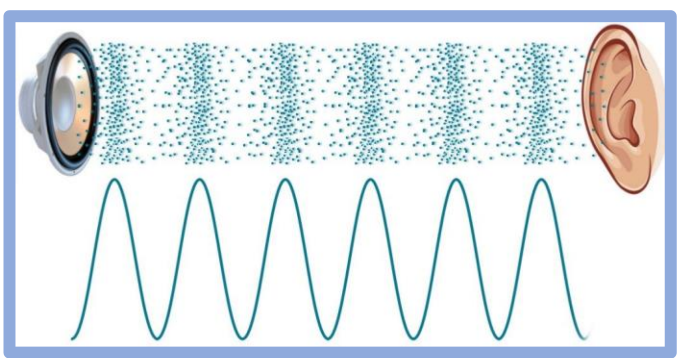
Sound Propagation



https://www.scienceabc.com/pure-sciences/movement-of-sound-waves-through-different-media.html