SONIC JOURNEYS:

A STUDY OF STUDENTS' CONCEPTUALIZATIONS OF SOUND AND HEARING

by

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ABSTRACT

This study was conducted to investigate changes in students' conceptualizations during the teaching of the following topics related to sound: 1) the characteristics of sound (frequency, pitch, frequency ranges, and uses of sound); 2) the transmission of sound; and 3) the reception of sound (the ear's anatomy and physiology). The study was conducted in a Science 8 class in a small British Columbia town. The students' conceptualizations were chronicled and categorized to show how they were influenced by classroom instruction and activities. Four students' conceptualizations during the unit were represented as *sonic journeys*, to show changes or maintenance of previously held ideas. Comparisons were made between the students' conceptualizations of various sound topics at the beginning, middle and end of the teaching. Additionally, comparisons of the four students' conceptualizations were made.

Students' conceptualizations were not static. Their ideas were influenced by the teaching and activities comprising the units on sound and hearing. Students developed *scientific* conceptualizations more readily for topics related to sound which were *concrete* (related to their immediate experience) than topics which were *abstract* (requiring non-experiential, theoretical explanations). Students' prior ideas continued to affect their conceptualizations throughout the course of the study. However, students did change their "ideas" as they became aware of their prior ideas and related them to the new concepts presented in the teaching. Thus *real* learning requires time for these conceptual changes to occur.

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CHAPTER I

THE PROBLEM

1.1 Introduction to the Problem

In the past two decades there has been much questioning about the purpose of science education and what students should be gaining from the experience. Some would argue that students should be exposed to a wide variety of information related to science. The emphasis on the quantity of information taught usually necessitates the teacher employing a *transmission* approach of instruction, rapidly leading the students through the curriculum with little regard for the students' learning styles or prior ideas. Recently, there has been some shift away from the transmission approach. Many educators focus more on the learner of science, recognizing the importance of the ideas and beliefs the learner brings to the science classroom (Gunstone, 1988). Instead of believing that students are *empty vessels* waiting to be filled with knowledge, students' prior ideas of the world are recognized as influencing how they learn in a science classroom.

1.2 Statement of the Problem Situation

Often students in the same classroom who are exposed to the same instruction will develop different ideas about science related concepts. Learning is a personal experience involving many factors including the students' experiences in the *real world* and the ideas that they have developed to explain their experiences. A major concern in science eduation is the non-scientifically acceptable views that students bring to class.

> These ideas / beliefs are frequently at odds with the ideas of science and can be held to tenaciously by students. This is shown particularly by the relatively common finding that students successful on standard forms of science achievement tests can fail to use this learned science to interpret everyday phenomena and analyze usual situations. Instead the interpretation and analysis are often undertaken with the ideas and beliefs held before encountering the science of the classroom (Gunstone, 1988, p. 73).

Gunstone and Watts presented an example of the influence of prior ideas for a physics graduate in a one year teacher training program who was shown a bell jar with a partially inflated balloon inside. When asked to predict what would happen when air was removed from the jar, he said, "The balloon will float" (1985, p. 86). His reason was "because the gravity will be reduced." A university science graduate will likely have completed five years of science courses during secondary school and another four years of post-secondary science courses. This illustrates that it is possible (and probable) that despite at least nine years of formal training, a science graduate may not have developed ideas that correspond to those accepted by the scientific community.

1.3 Purpose and Importance of the Study

Shapiro stated, "It is time that we build experiences and programs which incorporate this information [referring to individual student's prior ideas about and personal orientation towards science learning] to help students and teachers take action to learn and achieve a more positive experience in the science classroom" (1989, p. 733). A series of activities have been developed for this present study's investigation of four grade 8 science students' conceptualizations of sound and the ear's anatomy and physiology. The lessons and teaching strategies are based in part on Needham's idea (1987) that it is essential to take into account the students' prior ideas. First the students will learn about the characteristics and transmission of sound and then they will apply their knowledge of sound as they learn about the ear's anatomy and physiology. Yet, the focus of the study is not on the lessons and activities themselves, but on the students' ideas that result from experiencing the activities which comprise the lessons.

Many factors influence student learning. In the field of science education, much research has focused on students' prior ideas. The research has given evidence that many students have difficulty learning *scientific* explanations for natural events and cling to their prior *common sense* ideas (Osborne, 1985). Often in science education endpoints are measured (i.e. what the students know at the end of a unit or at a single point in time). Studies have dealt with students' ideas **either** before **or** after a series of lessons, but they have not focused on the **changes** in students' ideas before **and** after a series of lessons. Related to the problem of the non-scientifically acceptable ideas that students bring to class is the question of what students do to cope when their prior ideas are in conflict with those presented in the science classroom. If science educators are concerned about student learning, research should be conducted which investigates the difference between students' ideas before and following a series of lessons. Without identifying what the students knew at the start of a unit it is not possible to determine how the students' ideas changed by the end of that unit (i.e. what they learned). This present study of four students chronicles and categorizes the changes in their conceptualizations of sound, and the ear's anatomy and physiology during a series of science activities. The study highlights similarities and differences between the four students' conceptual developments. The purpose of this study is to examine the development of their conceptualizations and identify the factors which helped or hindered student learning, such as the influence of the students' prior ideas.

1.4 Research Questions

The aim of this study is to determine the nature of the conceptualizations of four science 8 students during units on sound, and the ear's anatomy and physiology. Listed below are the research questions.

General Research Question:

How do students' conceptualizations of sound and the human ear's anatomy and physiology change during and following a series of lessons?

Sub-Questions:

1) What are students' conceptualizations of the characteristics of sound before and following a series of lessons?

2) What are students' conceptualizations of sound transmission before and following a series of lessons?

3) What are students' conceptualizations of the human ear's anatomy and physiology before and following a series of lessons?

1.5 Scope and Delimitations of the Study

This study was conducted in a British Columbia grade 8 science class. The students were asked questions about sound and the ear's anatomy and physiology prior to beginning units on these topics. Their tests and quizzes were collected along with questions administered two weeks after the conclusion of the unit on the ear's anatomy and physiology. Based on the students' responses to the questions, their conceptualizations of sound and the ear's anatomy and physiology were categorized and tracked through the study.

Four grade 8 science students' responses to questions on tests and worksheets were obtained for the purposes of this study. They were willing to verbally clarify and expand on their answers to the questions about sound and hearing throughout the study. The students were cooperative and interested in having their ideas about sound probed.

This study has the potential of providing science educators with insights into what students' conceptualizations are and how their conceptualizations change as they learn about sound and the ear's anatomy and physiology. The study may highlight some of the difficulties students encounter in their efforts to develop *scientific* conceptualizations including the influence of the role of the students' prior ideas and experiences. Further, it may help identify the problems created for students' learning when the students are not aware of the teacher's purpose in sequencing and structuring lessons in a particular order (including the selection of demonstrations and student experiments).

1.6 Outline of the Remainder of the Thesis

This chapter has introduced the study and the rationale on which it is based. The following chapters deal with: a review of the literature (chapter II); the methodology (chapter III); the analysis of the data (chapter IV); and the implications of the research on teaching practice and science education research (chapter V). In the appendices the following information is provided: the lesson plans for the units on sound and the ear's anatomy and physiology and the schedule of the data collection; the teacher-researcher's predictions of how the four selected students' conceptualizations will develop during the study; the data gathering instruments including a complete set of one student's responses to the data gathering questions; and the first level of analysis of one student's responses to questions about sound and hearing upon which the theme for that student's sonic journeys was based.

CHAPTER II

REVIEW OF RELATED LITERATURE

2.1 Introduction

This literature review focuses on three main topics: 1) Piaget's theory of cognitive development; 2) the principles of constructivism; and 3) recent research and developments in science education including how constructivism has been interpreted and applied by science educators. Piaget's theory of cognitive development provides this present study of four science 8 students' conceptualizations of sound and the ear's anatomy and physiology with a framework for how individuals learn. The description of the principles that underpin constructivism is useful to this present study in two ways. First, the description illustrates some of the reasons why constructivism has been interpreted and applied by science educators to explain how students learn. Second, the description of constructivism addresses the content of *what* the students are learning, that is particular knowledge produced by a process called science. Following discussion of constructivism, findings based on research related to students' conceptualizations of science topics are presented.

2.2 Piaget's Theory of Cognitive Development

Jean Piaget provided a theory of cognitive development which fits the constructivist viewpoint (Inhelder & Piaget, 1958). His theory involves four main stages: the sensorimotor stage (birth to 18 months); the preoperational stage (18 months to 7 years); the concrete operations stage (7 to 12 years); and the formal operations stage (12 and older).

In relation to this present study of four students' conceptualizations of sound and the ear's anatomy and physiology, the concrete operations stage and formal operations stage are most pertinent. According to Piaget, the concrete operations stage occurs for children 7 to 12 years of age. In this stage children reason in terms of concrete realities, things they observe directly and their own personal experiences. They do not yet have the ability to think abstractly.

The formal operations stage occurs for children 12 years of age and older. Piaget says that during this stage, thinking becomes more logical, more abstract, and less egocentric than in previous stages. Without having to rely solely on concrete objects or personal experiences, the adolescent is able to think about abstract concepts and to discuss hypothetical situations and problems. Adolescents in the stage of concrete operations are limited to generating only one possible explanation for a problem. They are often ready to accept a hypothesis as true without examining its premises. Formal operational thinking enables a young person to reject an initial hypothesis more quickly than previously, when the evidence proves his or her initial idea to be incorrect. Furthermore, adolescents can solve verbal problems that are beyond the limits of younger children's concrete thinking.

According to Piaget, children develop more advanced reasoning as a consequence of alteration in mental structures called schemas. He defines a *schema* as a collection of data organized in a way that helps a person interpret the environment and new experiences. Upon encountering new experiences and new data, Piaget argues that people rely on their existing schema to determine their course of action and interpretations of a situation. In his theory, the actual changes in thinking take place through a process of equilibration. Equilibration works as follows. If a person applies a particular schema to an event or situation and the schema works, then equilibrium exists. If the schema does not produce a satisfying result, then disequilibrium exists and the person becomes uncomfortable. This motivates the person to accommodate, and thus her thinking changes. In order to maintain a balance between her schema and the information presented by the world around her, she continually assimilates new information using existing schemas and accomodates her thinking when necessary. Assimilation occurs when new information fits easily into existing schemas. Accommodation refers to the alteration of existing schemas or creation of new ones in response to new information. The process of equilibration is directly related to how students may deal with the information presented to them in class about sound and the ear's anatomy and physiology. One concern related to Piaget's ideas about equilibration is his assumption that people continually test their ideas. In relation to teaching science, the question arises as to how to motivate those students who do not test their ideas and thinking processes and thus do not experience disequilibrium. Without experiencing disequilibrium these students are not likely to be motivated to assimilate and/or accommodate the information presented in class.

In a modification of Piaget's original theories, Michael Berzonsky (1978) suggests that an adolescent person's experiences will determine the situations in which he or she will rely on formal or concrete thinking. Although Berzonsky agrees with Piaget that the sensorimotor, preoperational, and concrete stages are universal, he argues that adolescence offers a number of different cognitive tracks, only one of which is formal operational thinking (the ability to reason abstractly). According to the *branch model of cognitive development* (Dulik, 1972), all adolescents have the ability to develop formal operational thinking, but environmental influences will determine whether or not a youngster follows that particular cognitive track, or uses concrete thinking. Piaget admitted that the age at which children reach the stage of formal operations cannot be precisely predicted, so how do we know which young people have not yet arrived at the stage of formal operations?

Although most research on adolescent cognition has been conducted from a developmental perspective, some recent studies cast doubt on Piaget's theories. These studies question Piaget's position by demonstrating that the majority of adolescents and adults do not apply formal operations in any consistent manner. For example, numerous studies show that adults use concrete thinking to solve problems and that intelligent, well-educated adults do best when thinking about real, concrete problems rather than about abstractions (Kuhn & Brannock, 1977). Investigators have also found that young children employ certain aspects of formal thinking well in advance of the age predicted by Piaget (Keating, 1980). Data like these suggest that even if everyone has the potential to develop formal thinking during adolescence, concrete thinking is still the preferred choice in many situations throughout our lives. Other studies have challenged Piaget's theories on the basis that environmental influences affect whether people employ concrete or formal thinking. Among other potential environmental influences, studies suggest that cultural differences and educational experiences do advance or retard the development of formal operational thinking (Douglas & Wong, 1977).

While criticisms of Piaget's theory may be valid, his ideas provide a framework for the different ways that people construct knowledge. It is not surprising to find that people apply formal reasoning inconsistently, depending on the type of situation and problem. In relation to science education, it is not as important to know the exact ages at which a person is capable of operating at a certain stage as it is to know the possible levels at which a person is able to operate. In a science class students are asked to process a range of concrete and abstract information and they will likely use a range of cognitive strategies to cope with learning the concepts. Piaget has provided a description of the different ways a student may learn.

2.3 The Principles of Constructivism

During the past two decades, science education has applied the theory of constructivism to student learning. A description of the principles of constructivism is needed before exploring science education's interpretation and application of these ideas. In relation to constructivist theory, the literature surveyed has been that of constructivists who have strong and often controversial opinions about the process of scientific knowledge production. According to the literature, constructivist theory is rooted in the study of knowledge production (Segal, 1986). Mahoney (1976) claims that western culture places high value on knowledge. In efforts to find knowledge and truth, various knowledge forms have evolved and dominated over time. Constructivists make various claims about the purpose and process of scientific knowledge production. They focus on the process of knowledge production rather than the knowledge itself and argue that: 1) we do not have direct access to reality; 2) the role of the observer cannot be ignored in the production of knowledge; and 3) knowledge is constructed through a social process of generating shared meanings.

Watzlawick (1984) argues that different knowledge forms hold in common a basic assumption that a reality exists. In science, the pursuit of knowledge has been characterized as an attempt to find and explain reality. Von Glasersfeld states:

> In the philosophical tradition of the Western world, the concept of "knowledge" has almost without exception been understood to imply that the structures that result from cognition must in some way correspond to an external reality; "true" knowledge was supposed to depict or replicate what is real; and "reality" was intended to refer to a world "in-and-for-itself", a world that exists ready-made, fully-structured, and independent of any cognizing subject (1986, p. 107).

According to the literature, while constructivists accept that there is something that can be called reality, they argue that an incorrect, but commonly held view is that scientific knowledge is capable of giving us direct access to reality. Several constructivists state that the purpose of scientific knowledge production is to make representations of reality, because they argue that it is not possible to observe reality directly (Von Glasersfeld, 1986). Von Foerster claims that:

> We construct or invent reality rather than discover it. He suggests that we fool ourselves by first dividing our world into two realities -- the subjective world of our experience, and the so-called objective world of reality -- and then predicating our *understanding* on matching our experience with a world we assume exists independently of us (Segal, 1986, p. 17).

Von Glasersfeld (1986) agrees that knowledge is constructed from within an individual. He argues that the observations an individual makes are dependent on the person's ways of perceiving and conceiving. It is the individual who has the task of interpreting the information in order to achieve a "representation" of reality. Whichever way one looks at it, therefore, "knowledge cannot be a commodity that is found ready-made but must be the result of a cognizing subject's construction" (Von Glasersfeld, 1986, p. 109).

According to Von Glasersfeld (1986), in constructing knowledge we rely on sensory input which our brain processes to allow us to make representations of what we observe (e.g. the flame is hot; the curtains are blue; the music is loud). The tendency is for us to believe that what we observe **is** reality (i.e. that our senses give us direct access to reality). But according to Von Glasersfeld, what we observe is actually our representation of reality. For example, our sense of vision is often *deceived.* We look at a plane mirror and appear to be on the other side of the mirror. Somehow, we know this is not true. We close our eyelids and use our fingers to push on the eyelid and eyeball. We see patterns of light. Is this reality? We see water on the highway in the distance, but when we arrive there it is dry. Von Glasersfeld believes that these types of illusions indicate that we do not have direct access to reality and that the process of observing is interpretive. In addition to sensory illusions, Nadeau and Désautels (1984) argue that the language and symbols used to construct scientific knowledge also limit our representations of reality.

D'Abro (1951) thinks that the scientific conception of reality stems from the seventeenth century concept of causality which he believes has greatly influenced how scientific inquiry is conducted. The concept of causality (commonly called cause and effect) refers to the idea that the same causes generate the same results. D'Abro (1951) says that the "doctrine" of causality seemed to answer human's search for certainty and objectivity. The philosophers and scientists of the sixteenth and seventeenth century thought they had avoided the problem of objectivity. They developed procedures for *objectifying* observation to exclude human bias using a process called the *scientific method.*

In textbooks used for classroom instruction the scientific method is typically presented as consisting of these steps: observing events; formulating a question about the events; developing a hypothesis to answer the question; designing and conducting experiments to test the hypothesis along with observation; drawing and reporting conclusions; moving onto another question (Creager et al, 1985). Within these steps are feedback loops to allow modifications at any stage. When discussing the scientific method constructivists are concerned about the process of observation and how scientists define the term *objectivity.*

In relation to the production of scientific knowledge, a scientific explanation is called valid if the experiments upon which it is based can be replicated and yield the same findings. According to this view, scientific findings are said to be independent of the person who does the research, and thus these findings are called objective findings. If the research is replicable, the scientific community decides that a *discovery* about reality has been made rather than a construction by the observer (Segal, 1986, p. 19). Nadeau and Désautels (1984) believe that the scientific method gives the false impression that there is a recipe for producing knowledge, that knowledge production is a certainty if the scientific method is followed. According to Nadeau and Désautels what the scientific method may actually describe, in simplified form, is the process that new knowledge must undergo after it has been produced. The authors say that the new knowledge is then *packaged* in accordance with the scientific method in order to be accepted by the scientific community. Nadeau and Désautels think that teachers and textbooks often fail to make the distinction. The scientific method is not a recipe for knowledge production, but a decision-making tool for assessing a knowledge claim.

Constructivists think that the scientific community gives an incorrect view of scientific knowledge providing an objective view of reality, with *objective* meaning independent of the observer. Von Glasersfeld (1985, p. 97) says, "An objective view or judgement has come to characterize also a view or judgement of which one thinks that it is not biased by specific individual quirks or preferences and would therefore be shared by others under the same circumstances." Von Glasersfeld describes his view of the purpose of knowledge production as follows:

> Instead of the paradoxical requirement that knowledge should reflect, depict, or somehow correspond to a world as it might be without the knower, knowledge can now be seen as <u>fitting</u> the constraints withing the organism's living, operating, and thinking takes place. From that perspective, then, "good" knowledge is the repertoire of ways of acting and/or thinking that enable the cognizing subject to organize, predict, and even to control the flow of experience. From this changed point of view, then, the cognitive activity does not strive to attain a veridical picture of an "objective" world (a goal which, as the skeptics have always told us, is unattainable), but it strives for <u>viable</u> solutions to whatever problems it happens to deal with (1986, p. 108).

A key component of the scientific method is observation. Constructivists believe that it is mistakenly thought that observing is an objective act rather than an interpretive process. One of the reasons for such a view is described by Elkind:

> Once a concept is constructed, it is immediately externalized so that it appears to the subject as a perceptually given property of the object and independent of the subject's own mental activity. The tendency of mental activities to become automatized and for their results to be perceived as external to the subject is what leads to the conviction that there is a reality independent of thought (1958, pp. xi-xii).

Instead, constructivists characterize observation as an interpretive process that varies between individuals. Constructivists question how the term *objective* is used in relation to the production of scientific knowledge. A constructivist theory of knowledge argues against this definition of objectivity in scientific knowledge production. Does it matter who does the observing and interprets the data? Constructivists think that it does matter and wonder how the process of developing scientific knowledge can ignore the role of the observers themselves (the scientists) who do the science. Popper (1972) argues that observations should no longer be seen as objective, but influenced by the ideas of the observer. This means that scientists will likely focus on different aspects of the experiment and generate different observations and data.

Nadeau and Désautels (1984) reject the idea of the scientist as an objective being, separate from the investigations she makes. They argue that science is a social activity and that, while a scientific theory may appear to be an individual's work, the process that leads to the theory is a group effort. In their definition of objectivity, Désautels and Nadeau say that the only requirement is that it be possible to test the hypothesis for the purpose of verification. Rather than a quest for the *truth*, they see this verification process as an attempt to determine what to do with the hypothesis (i.e. reject it, keep it, ignore it temporarily).

Constructivists do not believe that scientific 'findings' are objective as they require the subjectivity of an observer to interpret the meaning of what they witness. Von Foerster states:

> The constructivists challenge the idea that we match experience to reality. They argue that we need not assume "objectivity" to do science. No findings exist independently of observers. Observing systems can only correlate their sense experiences with themselves and each other (1981, p. 295).

Many people still see the world like seventeenth century scientists, assuming that it is possible to have objectivity and to know reality (Segal, 1986). Von Foerster (1981) claims that while we usually know what we think we know, we can never know for sure if others truly share our meanings. We can only go by what they say they mean. For example, if I am shown a block and say its colour is green and other people agree that it is green that is all we have agreed upon. We cannot know for sure that our representations of green are the same because this would require having the capability to use each others' nervous systems. Segal says, "we never know what goes on in other people's heads. So it might be more accurate to say that we match our perceptions against what other people *say* about their own" (1986, p. 15).

In sum, constructivists challenge the traditional conception of objectivity conveyed by the scientific community which presumes that there is an external reality that is directly knowable and *waiting to be discovered* and ignores the role of the observer in the construction of knowledge. Constructivists do not think reality is directly knowable, and that what is often taken for reality are our representations of reality that we construct in a social process. Von Glasersfeld (1986) believes that not enough attention is given to the process of knowledge construction, and too much attention is focused on what is discovered and the person credited with the discovery.

Constructivists think that knowledge comes from within an individual through an interpretive process that is influenced by the individual's prior experiences, assumptions, and methods of cognizing. These ideas are mirrored in recent findings in science education research on students' conceptualizations, discussed later in this chapter. In sum, constructivists do not accept knowledge at face value. They want to know how the knowledge was produced and the context in which it was generated.

2.4 Recent Research in Science Education

In this section, the literature review explores the developments in science education over the past few decades. Information is presented about the following topics in science education research: 1) the purpose of science education; 2) the process of learning; 3) factors which influence student learning; 4) a summary of the findings in research which investigated students' conceptualizations of science topics; 5) various approaches to teaching science; and 6) a study of conceptualizations of sound.

2.4.1 The Purpose of Science Education

The purpose of science education remains a fundamental question for science educators. Is it to fill students' heads with information from the great book of knowledge accepted by scientists? Is it for students to understand the process of producing knowledge that is called scientific knowledge? There is no simple answer to the question of science education's purpose. The purpose varies not only from country to country, but also from teacher to teacher, even those working in the same school. Some science teachers might argue that the purpose of science education is to expose the students to a large volume of information. Other science teachers might argue for the discovery approach to science education in which students conduct experiments and discover fundamental scientific laws. Still other science teachers might view the purpose of science education as being for the students to conduct science, that is to attempt to produce knowledge. In the latter approach students develop questions about the world around them and then attempt to devise methods of testing their explanations for these questions, with no guarantee of actually producing knowledge.

From a constructivist perspective, the purpose of science education is to find ways which help students build on their prior knowledge. In the constructivist view, as applied to science education, the student is no longer seen as a passive receiver of information. This change creates a radical shift in how knowledge is defined. The traditional view of the purpose of science education has been to *cover the curriculum* focusing on teaching a large volume of concepts throughout the school year. In more recent years, another purpose for science education has developed, for students to develop clearer conceptualizations of science concepts. According to the constructivist perspective students should explore their own conceptualizations of science concepts and build on these conceptualizations. In the latter case more time is needed to teach the concepts in a reflective process. The difference between the two positions is that the traditional view focuses on *how much* the students know, whereas the constructivist perspective focuses on *how well* the students know what they know.

2.4.2 The Process of Learning

There is some agreement between psychologists and educators about the constructive nature of the learning process. Despite this, "many teachers tend to assume that when they have taught something by outlining it verbally (perhaps just once) it will be learned by those who heard or read it in the intended way" (Freyberg and Osborne, 1985, p. 84). The assumption that students immediately understand what has been taught is made particularly by beginning teachers who focus their attention on their own mastery of the curriculum, rather than on the students' learning. Wittrock's (1974) view of teaching and learning is that learners actively construct or generate meaning from sensory input and it is the teacher's job to find ways that the learner will create new meanings that will be useful to him or her. Paralleling the earlier discussion of constructivism in which it was argued that observations are not independent of the observer, Driver states: "Evidence and data can be *discovered* but an interpretive framework is a construction of the mind and has to be *invented*" (1983, p. 42). Freyberg and Osborne (1985) argue that experiences play a greater role than age in how children process information. The consensus among *constructivist* science education researchers is that for learning to occur it must be an active process of making meaning and that knowledge is constructed within an individual.

A variety of models for how knowledge is constructed by students have been proposed. An example of this is Osborne's and Wittrock's generative learning model (1983). They propose that: 1) the learner's memory and sensory input work together to select some and ignore other stimuli; 2) the selected stimuli has no meaning before the learner gives it meaning; 3) the learner creates meaning by generating links between the stimuli and his/her memory; 4) the learner retrieves information from his/her memory and uses this information to construct meaning from the sensory input; 5) the learner may test the constructed meaning; 6) there will be some status (or worth) attached to the constructed meaning. The model fits the constructivist position that the construction of knowledge is a personal and subjective process. Osborne and Freyberg (1985) acknowledge that Osborne and Wittrock's model oversimplifies the process of learning. They think the value in using this model is that it emphasizes that the learner's responsibility is to learn, generating links between sensory input and prior ideas.

Much of the research literature characterizes conceptual change as a slow, long-term process. Initially, the learners interpret a new situation in terms of what they already know and reinforce their prior ideas. In order to achieve conceptual change, the learner must view the new conception as useful and plausible and the prior conception must also be seen as no longer useful. Hewson (1981) thinks that any change from one viewpoint to another must be a gradual process so that prior ideas have time to lose status as they beome less intelligible, plausible and fruitful. Osborne, Bell and Gilbert (1983) argue that it is often the scientist's conception that is less intelligible, plausible and fruitful than the students' prior ideas. Thus it is not surprising that students cling to their prior ideas.

A number of links between constructivist theory and science education can be defined: 1) scientific knowledge production and learning are both interpretive processes in which people attempt to observe and explain reality; 2) knowledge is produced from within individuals, based on their prior experiences and assumptions; scientists and students attempt to fit their explanations with their experiences and these will differ between individuals; and 3) educators can only make assumptions about what they think the students know.

2.4.3 Factors Which Influence Student Learning

2.4.3.1 The Influence of Students' Prior Ideas

Science teachers are now concerned about the non-scientifically acceptable views that students bring to class. According to the literature, this concern is justified because students' prior ideas will influence their conceptual changes. Bell (1993) provides examples of the names applied to these non-scientifically acceptable students' ideas about the world around them: misconceptions; alternative conceptions; alternative frameworks; preconceptions; children's science; intuitive ideas; and untutored beliefs.

There are many examples of students' alternative conceptualizations in the research literature. For example, when asked to discuss gravity, a 14 year old said, "The higher up you go, the stronger the gravity is until you get out of the atmosphere" (Freyberg and Osborne, 1985, p. 87). (This conceptualization may be based on the observation that objects that fall from a greater height travel at higher speed before impact with the ground). Based on his studies of students' conceptions of heat and temperature, Erickson concluded:

> Many children appear to have constructed various simple explanations to account for everyday situations they encounter involving heat and temperature. These explanations may subsequently become an integral part of the child's explanatory framework when she or he is faced with similar sorts of problems in a school setting (Erickson & Tiberghien, 1985, p. 52).

In activities related to electric circuits, Tasker and Osborne provide examples of student responses to the question, "Where does the electric current which goes into the lamp go? Students state: "It goes back to the power source"; "It goes on around the circuit; "It is used up"; "It goes out as energy in the lights"; "It gets burnt up" (1983, p. 139). Some of the responses fit the scientific conception, while others are examples of students' alternative frameworks. Driver (1985) states that ten percent of 11-year olds in Britain include the sun, wind and fire in the concept of 'living things'. Gunstone and Watts present an example of students' conceptions of gravity:

> The students were asked to predict and compare the times taken for one-inch cubes of plastic and aluminium [aluminum] to fall about two metres. Lou answered: 'The heavier [aluminum] one will get there first.' . . . Lou's belief that the aluminium [aluminum] would fall faster was apparently so strong that it influenced his observation (1985, p. 87).

Another finding mentioned widely in the literature is that students hold on to their existing ideas strongly. For example Driver says:

> An idea or framework will not be rejected until there is something adequate and reliable to replace it with. Pupils can be given experiences which conflict with their expectations, but those same experiences do not of themselves help the pupils to reconstruct an adequate alternative view of the system (1983, p. 41).

Before students can be expected to adopt new ideas and reject their old ones, they must be able to understand the new ideas presented to them. Further, these ideas must be so useful to the students that they are motivated to abandon their prior ideas.

Students will often cling to their prior ideas, ideas that meet their needs in explaining natural phenomena but do not match the scientific conceptions. Students commonly explain events in the real world based on their prior ideas, and use their science knowledge in the classroom to meet the teacher's expectations (Gunstone and Watts, 1985). In the classroom, students' prior ideas often conflict with the scientific conception. These prior ideas may have served the students well in their day-to-day lives, but often what the students are asked to do in class is *erase* their prior ideas and accept the explanations of science. An alternative approach to science education would be to have the students think about phenomena in detail that they may have taken for granted. Rather than *erasing* students' prior ideas and replacing them with the ideas of science, Driver argues that "the teaching of science in schools is a process whereby students reconstruct their understandings in ongoing conceptual change" (1988, p. 133).

2.4.3.2 The Problems of the Unobservables

One major obstacle for students learning science concepts is the "problem of the unobservables" (Schollum and Osborne, 1985) which arise from scientific explanations of events that cannot be observed. There are many situations in which scientific explanations are used for events that cannot be observed. Chemistry provides examples of this type of problem. Explanations of chemical reactions centre around the building block of matter, the atom. When students watch sodium flare up on contact with water and hear a small explosion, the explanation given is that the sodium has lost an electron to become a more stable sodium ion. This explanation may not fit easily into students' ideas about how chemical reactions occur. Further, when told that rusting is also a chemical reaction it may be difficult for students to understand how the explosion and rusting are based on the same basic interaction of atoms' electrons. These are abstract concepts, and attempts to explain them visually often rely on models to illustrate what happens during a reaction. Here the problem of unobservables is that we do not have the capability to observe what happens to atoms involved in a reaction. Driver summarizes it this way:

> It is possible that students have constructed ideas about atoms and molecules, and their symbolic representation in the way intended in science lessons, but when presented with a physical phenomenon to explain, students tend not to see these taught ideas as relevant using instead their intuitive ideas based on experience. The issue which needs to be considered is not just whether students understand the theoretical ideas or models they are exposed to in teaching but whether they can use them or see them as useful and appropriate in interpreting actual events (1985, p. 168).

Driver, Guesne, and Tiberghien go on to state:

> In teaching science we are leading pupils to 'see' phenomena and experimental situations in particular ways; to wear scientist's 'conceptual spectacles'. This involves pupils in constructing mental models for entities which are not perceived directly, such as light, electric current, particles of matter (1985, p. 193).

2.4.3.3 The Problems of Mismatches for Student Learning

Language is the medium in which scientific ideas are expressed. It is also the medium in which teachers instruct students, as they guide them through experiments or explain concepts. Students use language to express their conceptions and teachers use these conceptions to assess their students' level of understanding. Language, however, creates a variety of obstacles which interfere with how students construct and express knowledge, and how teachers interpret what they hear the students saying. Bell and Freyberg (1985) describe some of these problems which occur when a word has one meaning for the teacher but a different meaning for the student. Many times the students are unaware of the mismatch. For example, in science the term light refers to a form of energy. But students may use the common interpretation of the word light referring to a light bulb. (This ignores other meanings for the word light, such as *low weight.*) Mismatches can create problems for students as they try to construct knowledge. The mismatch may be identified by the students but they may continue using their own meaning rather than the one presented in class. When students express their ideas to the teacher using the technical terms of science it can lead to the impression that they understand what they are saying. Bell and Freyberg call this "making noises which sound scientific" (1985, p. 33). Problems in students' conceptualizations also occur when teachers use language that is unfamiliar to the students. It may be that the teacher mistakenly assumes that the students are familiar with the technical terms. In other instances, it may be that teachers rely on the technical terms of science when their own understanding of concepts is unclear. Teachers may mask their own difficulty with the material which results in poor communication with the students.

Bell (1993) states that the common meanings for words tend to shape children's constructions. The language of science is often slightly different from the everyday language of society, and this can create confusion in meaning. She gives the terms 'animal', 'friction', and 'force' as examples. In science terms, humans are considered to be animals. In everyday terms, humans are often portrayed as being different from animals. Bell says, "Children will often endow an object with a certain amount of a physical quantity and this quantity (e.g. force, momentum, energy) can give an unwarranted material reality" (1993, p. 20). Children are not alone in doing this. One only needs to hear a baseball announcer say, "That ball had a lot of *velocity on it* " to get the impression that velocity is something carried on a baseball like dirt.

Related to the problems of language are the general problems of communication in a classroom between the teacher and students. Tasker and Freyberg (1985) summarize some of the mismatches in the classroom as: discrepancies in intent; discrepancies in action; and discrepancies in the views of the world. Discrepancies in intent are characterized as the difference between how the teacher and students view the lessons. Teachers often develop a particular order of lessons to provide sequenced information about a concept. They view these lessons as logical with each lesson building on the one before it. Frequently the links between lessons are not seen by students who view the lessons as isolated events. Further, the purpose of experiments may be clear to the teacher but unclear to the students who may decide the experiment has a completely different purpose. Discrepancies in action refer to the differences between what the teacher expects the students to be doing in an activity or an experiment and what the students think they should be doing. If the students are unclear about what they are to do in an experiment they may resort to guessing what the teacher wants them to do, and abandon procedures in a bid to get the *right answer.* Discrepancies in the views of the world refer to the difference in what the teacher expects the students to learn from an activity and what the students actually learn. This discrepancy comes about when teachers expect students to make great leaps from data gathered in class to develop appropriate conclusions which resemble scientific laws. The data the students gather may be different from what the teacher expects and this makes drawing the expected conclusion impossible. In some instances the students' data may not even be logically connected to the scientific law or pre-determined conclusion. Such discrepancies can readily confuse students as they perceive gaps in how the conclusions were drawn. To address the problems created by mismatches in the classroom, Tasker and Freyberg (1985) argue that the teacher's mission should be: to make sure that the intended purpose becomes the student's purpose; to make sure the activity is understood and accepted in advance by students; and to value the pupil's conclusions and discuss and relate these to the teacher's hoped for conclusion.

2.4.4 Summary of Findings in Conceptualization Research

In science education, numerous studies have investigated students' conceptualizations of scientific phenomena. Initially, this conceptualization research focused on physics topics, mainly electricity, heat, and force and motion. The research has broadened to include other areas such as biology and chemistry. Many of these studies have been of students ranging in age from eight to fifteen years old.

From research on children's ideas in science some general statements can be made: children create meanings for many words used in science teaching and conceptions about the world they live in that relate to ideas taught in science; children's ideas are usually strongly held and often differ significantly from the views of scientists; these ideas are sensible and coherent from the children's point of view, and science teaching often fails to change them or affects them in unanticipated ways (Osborne and Freyberg, 1985).

Gunstone discussed several consistent findings based on research which probed students' conceptualizations of science topics:

> 1) When students come to formal science learning they frequently already hold explanatory views of phenomena which are apparently personal and idiosyncratic interpretations of experiences and are often different from the explanatory views taught in the classroom;
>
> 2) These views can be remarkably unaffected by traditional forms of instruction;
>
> 3) Particular views can be quite common . . . that is, the finding of these idea/beliefs is not a function of the sample of the students involved and one view can be held by many students; and
>
> 4) Some students can hold the scientists' interpretation given in instruction together with a conflicting view already present before instruction. The science interpretation is often used to answer questions in science tests, and the conflicting view retained to interpret the world. (Gunstone, 1988, pp. 74-75).

In sum, the science education interpretation of constructivism centres on the learners taking the lead role in the construction of their knowledge. The learners' prior experiences and ideas have a powerful influence in relation to how they construct new knowledge.

2.4.5 Various Approaches to Teaching Science

Baird (1988) believes that research and development efforts in science education over the last few decades have had little effect on science teachers and science teaching. He blames the ineffective transfer from theory to practice in education on a lack of understanding about what teaching is and how it works. In the past few decades there has been a shift toward alternative methods of instruction. One such change has been toward the *discovery* method which emphasizes more experimental work so that students can learn science by doing it. Baird described the shift from the *confirmation* approach to the *discovery* approach as a positive step.

In the discovery method, students attempt to *discover* key theories of science by conducting experiments in which they get the *expected* result and develop the same conclusions as past scientists. The observer's way of seeing the world is not taken into account. Driver (1983) opposes the discovery approach to teaching. She argues that it has two contrary objectives. On the one hand, the students are expected to demonstrate their curiosity as they investigate a phenomenon. On the other hand, the students are expected to converge on an *expected* scientific law as they search for the *right* answer. The students are expected to experience the excitement of acting *like a scientist* in an activity where diverging results are likely, yet the students are supposed to make similar conclusions. She argues that it is unrealistic to expect students to discover or formulate scientific laws based on the experiments they conduct in class.

Similarly, Tasker and Osborne (1985) think there are several problems with the discovery approach. Based on studies they conducted with students investigating electricity, they cited the following problems. There was a disparity between: the *ideas* children brought to the lesson and the ideas the teacher assumed that they would bring to it; the *scientific problem* the teacher would have liked them to investigate and what the students took to be the problem; the *activity* proposed by the teacher and the activity undertaken by the children, despite considerable teacher intervention; the children's *conclusions*, and the conclusions proposed by the teacher (Tasker and Osborne, 1983).

To address the difficulties students' alternative conceptualizations create for science teachers, Driver (1983) suggests that teaching programs should be designed to take into account both children's ideas and those of the scientific community. This sentiment is echoed in other studies. Fensham (1980) introduced the term, "student dominance." He believes that children's science should play a greater role in curriculum development. Children's science refers to the ideas that children bring to class, their prior conceptualizations.

The shift to a constructivist approach to teaching also necessitates a change in how the students are viewed. Instead of believing that students are *empty vessels* waiting to be filled with knowledge, the students' prior ideas of the world are taken into account before and during the learning activities. The educator focuses more on the learner of science, recognizing the importance of the ideas and beliefs the learner brings to the science classroom.

> These ideas / beliefs are frequently at odds with the ideas of science and can be held to tenaciously by students. This is shown particularly by the relatively common finding that students successful on standard forms of science achievement tests can fail to use this learned science to interpret everyday phenomena and analyze usual situations. Instead the interpretation and analysis are often undertaken with the ideas and beliefs held before encountering the science of the classroom (Gunstone, 1988, p. 73).

The constructivist literature in science education is in agreement that students have prior ideas about phenomena in the world around them and that the starting point in teaching is to determine what these prior ideas are. Osborne thinks that the curriculum often seems to be made without regard to student's prior ideas and that altering the order of curriculum may yield more effective learning (Osborne, 1985). Osborne places three conditions for how effective instruction should be developed: 1) help children exchange, evolve or extend their existing ideas with respect to a particular topic; 2) present new ideas so that they appear intelligible, plausible and useful to the learner; and 3) order the topics of the curriculum better to take into account the learner's intuitive and/or developing ideas (Osborne, 1985, p. 41).

Schollum and Osborne (1985) make the case for relevance by relating science to everyday events, and presenting the world outside the classroom in a way that is useful to the student. Along these lines, White (1979) argues that experiments should use everyday objects, rather than laboratory equipment so that school science is more easily linked to everyday life. Gunstone and Watts (1985) believe that experiments should be conducted not to verify the laws of science but to challenge the students' prior ideas.

Bell and Freyberg (1985) suggest that one way to solve the language problem in the science classroom is for students to work in small groups and verbalize their ideas in science so that they better understand their own views. They argue that if students are expected to change their views, they must know what their original views are. Driver (1985) takes the students' prior knowledge into account by providing opportunities for the students to make their own ideas explicit so that they recognize their own conceptualizations. She adds that activities should focus less on getting the *right* answer and more on encouraging students to use a range of conceptual schemes. She states:

> It is worth reflecting briefly on the change in thinking that this involves for children moving from reasoning which is perceptually dominated . . . to conceptually dominated thinking (Driver, 1985, p. 145).

Driver (1983) argues that experimental work can involve more than the traditional forms of illustrating scientific principles. She thinks that it would be useful for students to do their own experiments to gain experience in designing and conducting an experiment in an honest and thorough way. Driver suggests that if students designed and conducted their own experiments, they would have greater opportunities to reflect on their own thought processes as they use their initiative and imagination. Such work is time-consuming, but she believes it is worth taking the time to utilize this approach, "curtailing the syllabus is not too great a price to pay if as a result pupils gain greater confidence in their understanding of the ideas covered" (Driver, 1983, p. 84).

2.4.6 A Study of Conceptualizations of Sound

In science education there have been numerous studies of students' conceptions of such physics topics as heat, force, and electricity, but few studies of sound. However, Linder's "A Case Study of University Students' Conceptualizations of Sound" (1989) is a study of ten graduate physics students who were in a university physics teacher education program. The study investigated and identified some of the conceptual problems that university physics students dealt with when asked to explain their understanding of sound based on what they studied in the undergraduate physics courses. In Linder's study the technical level for the student teachers' explanations was much higher than that expected of the grade 8 students in this present study.

Linder (1989) states that it is not surprising to find that students have fragmented knowledge following physics instruction that does not allow enough time for reflection and consolidation. He argues that the curriculum for university physics is too broad, created in an attempt to meet the demands of different physics specialties requiring that their curriculum be emphasized.

> When a group of education students, who are physics graduates, display conceptual dispersion about physics fundamentals the question arises: how is it that their knowledge base appears to be so fragmented? While such a state of affairs may be both conceivable and understandable at school level it would seem to be enigmatic at a graduate level (Linder, 1989, p. 160).

Linder argues that a basic goal of physics education should be to:

> simultaneously create an environment where students' sense making is acknowledged and respected, and to generate a repertoire of experiences that can both individually and collectively provide a functional referential framework to facilitate the evocation of contextually appropriate conceptualiztions; thus both recognizing and rationalizing their conceptual dispersion (1989, p. 165).

He argues that in order to allow students to express and probe their own physics conceptualizations, more time and smaller class sizes are required. Linder thinks more time is essential to allow students the opportunity to explore their own physics conceptualizations so that they can better recognize any inconsistencies. The present study investigates the changes in conceptualizations that occur over time as the students proceed through a unit on sound and how students develop their conceptualizations of sound. Linder's view that "it is more important to focus on *how* students make sense of *what* they are being taught rather than how widespread a particular conceptualization is" (Linder, 1989, p. 172) is implemented in the present study.

2.5 Summary

The present study is of four grade 8 students' conceptualizations of sound and hearing. Piaget's concrete operations and formal operations stages of cognitive development are useful because they provide insight into how students this age think. The study focuses on how students construct knowledge about the concepts of sound, hearing and the human ear. The principles of constructivist theory together with science educators' interpretations and applications of the theory informed the researcher about the difficulties created when facilitating conceptual change.

Gilbert, Osborne and Fensham (1982) outlined several possible outcomes when teaching students: 1) an undisturbed children's science outcome; 2) a two-perspective outcome; 3) a reinforced outcome; 4) a confused outcome; and 5) a unified scientific outcome. In the present study these outcomes were modified to categorize the four grade 8 students' conceptualizations of sound, and the ear's anatomy and physiology. Most research studies focused on students' conceptualizations at one point in time and none tracked students' conceptualizations throughout a science topic. However, the present study tracks students' conceptualizations at several stages during the teaching of topics related to sound.

While the problems associated with generating conceptual change in science education are described in the literature, the question remains, how does one accomplish this task? Before tackling this question, it is necessary to study the process of conceptual change directly, rather than conceptualizations at a single point in time. This study investigated the changes in students' conceptualizations of sound, and the ear's anatomy and physiology as they moved through lessons on these topics. The intent is to gain insight into the process of conceptual change.

CHAPTER III

DESIGN OF STUDY AND METHODOLOGY

3.01 Introduction: Overview of a Qualitative Case Study

This study investigated students' conceptualizations of sound, hearing and the human ear. The study explored students' conceptualizations before, during and following a unit on the following topics related to sound: 1) the characteristics of sound (frequency, pitch, frequency ranges, and uses of sound); 2) the transmission of sound; and 3) the reception of sound (the ear's anatomy and physiology). The unit featured the characteristics and transmission of sound followed by two applications of what the students had learned. The first application involved classroom instruction on the human ear's anatomy and physiology. In the second application the students designed a hearing device to repair some form of damage to the ear. This present study represented students' conceptualizations during the unit, showing changes or maintenance of previously held ideas.

3.02 Description of Methodology

The study involved a teacher conducting research of four grade 8 science students in a small British Columbia town. The study was qualititative in design, based on a combination of the work of Shapiro (1989) and Linder (1989). Shapiro investigated students in grade 5 who studied light. She explains that initially she planned to investigate the students' ideas about light, but instead looked for underlying reasons why some children in a class changed their ideas while others did not, even though all the students in the class received the same instruction. She argues that the student's personal orientation to science is a powerful influence on student conceptual change. Shapiro says that it is more important for educators to involve students in exploring their own ideas about a science topic rather than developing any set of teaching techniques that might magically allow students to develop a *scientific* conceptualization. Originally I planned to develop an alternate approach to teaching a unit on sound. As the study evolved the focus shifted to an investigation of students' conceptualizations as they progressed through units on sound and the ear's anatomy and physiology. I asked the students to probe their own ideas throughout the study.

This present study is similar to Linder's in that both studies explore individuals' conceptualizations of sound. A notable difference between the two studies is in the choice of subjects. Linder selected university students who were in the final year of training to become science teachers, specifically physics teachers. My students were in grade 8. This difference led to different expectations of what the subjects' should know about sound. Linder's subjects provided sophisticated conceptualizations, laden with the jargon and the mathematics of physics, while my selected students used the language of their age-group and the grade 8 science textbook. Linder probed his subjects' conceptualizations after they had been exposed to many years of formal science and physics education while the students I selected were at an earlier stage in their formal education process. Further, this present study investigated how the students' conceptualizations changed during a unit on sound, hearing and the human ear, whereas Linder's study asked the students' to reflect on their physics education, particularly university.

3.03 Pilot Study

A pilot study with six Science 8 students was conducted in which the students' worksheets, tests, and projects were developed and collected. At three stages (before, during and following the unit on sound and hearing), the students were interviewed about their responses to questions on the tests and worksheets. The intent was to analyze the students' conceptualizations while the unit was taught. However, this was not possible. Based on the pilot study, I decided to abandon audiotaped interviews for three major reasons. Demands on my time as a teacher and investigator, as well as demands on the subjects' time, made the interviews impossible. The time needed to transcribe the volume of audiotape was more than my schedule would allow. Additionally, I did not want to treat the selected students differently from the other students in the class by selecting some for interviews. I also learned that I was not a skilled interviewer. I found myself asking *leading questions* or wanting to teach the students during the interviews. In the study I limited my interviewing role to clarifying what the students reported on the tests and assignments.

Following the pilot study I examined and revised the test and assignment questions to make them clearer and ensure that I could track the students' ideas throughout the study. One significant revision was the incorporation of the concept of *sound particles* into questions about sound transmission. *Sound particles* refers to the idea that sound is a physical substance that travels in the form of particles that move through other media. Although the idea of *sound particles* does not fit the scientific perspective, several students in the pilot study included *sound particles* in their descriptions of sound transmission. I thought the inclusion of *sound particles* would provide an indicator of whether students were able to describe the complex nature of sound transmission or relied on the idea that sound travelled like a physical object.

The pilot study provided insight into the importance of transcribing the data into a usable form. The pilot study focused on making the data collection and transcription more efficient. In the study, *question templates* were made for each subject ahead of time. Question templates refer to the questions from each data collecting instrument used to track the students' conceptualizations throughout the study. The questions for a particular topic were written in sequence (i.e. prior questions then midpoint questions then final questions). As the students' responses were generated the data were readily entered on the computer. Interviews were conducted in class and consisted of informal questions to make sure that I interpreted subjects' responses as they intended. As I entered the students' responses during data transcription I noted any responses that were unclear to me. Then in class I asked the students individually to explain verbally what they had written or drawn and I recorded this information directly on their tests and assignments. In this way I was assured of the appropriateness of my interpretations. I interviewed all twenty-four students in the science 8 class (not just the four selected students) in the same way to maintain a sense of impartiality.

3.04 Context of the Study

The study was conducted in a grade 8 science class in a secondary school with a student population of approximately 500. The school was located in a small British Columbia town whose economy was dominated by the forest industry. In the school there were five classes of Science 8, with approximately 24 students per class. I taught two of the five Science 8 classes. Prior to the unit on sound we had investigated the following topics:

1) Safety / Use of Lab Equipment

2) Chemistry
   - Kinetic Molecular Theory of Matter
   - Properties and Uses of Matter
   - Chemical and Physical Changes
   - Classifying Matter

3) Energy
   - Forms of Energy
   - Heat Energy

3.05 Selection of Subjects

The study was conducted midway through the school year which facilitated familiarity with the students and opportunities to assess their level of interest, effort and ability in science. From one of the two classes I taught I selected 8 students whom I expected would complete all the activities involved in this study and provide interesting data. I based the selection of the students largely on examination marks for the first two terms. Their grades on homework, classwork and lab assignments gave me an indication that they would complete all the activities in this study. For most students, their marks on homework and lab reports were higher than on tests. Their overall term marks were usually higher than their test marks. I chose students with a range of abilities and decided that test scores provided the clearest indication of ability. All the students had passing marks ($\geq 50\%$) both for the course and on tests. Student marks on tests ranged from 56% to 90% in the first term and 53% to 90% in the second term.

In the present study I selected four students whose ideas about sound and the ear's anatomy and physiology I expected to develop in different ways. For just those four students I made brief predictions as to how I thought their conceptualizations of sound and hearing would develop. Three of the four students were in the school band. This is worth noting as their experiences playing music will have influenced their conceptualizations of sound. In the pilot study I studied six students' conceptualizations of sound and hearing. Unfortunately, the volume of data generated proved to be too great to probe in detail. In the pilot study not all the selected students completed the activities so in this study I selected four additional students, bringing the total to eight, to ensure that at least four students would complete the required activities. I selected four males and four females and while student gender was not the focus of this study, I wanted to investigate how both males and females develop conceptualizations of science topics. In the study six of the eight students completed the required activities including all four students' whose ideas I originally planned to investigate. I reported on those four students.

3.06 Instrumentation

Five instruments were developed to track the students' conceptualizations of specific sound-related topics throughout the study. Copies of the instruments which feature one student's particular responses to the questions are included in the appendix. Questions were designed to help students express their ideas about sound in more than one word yes-no responses. For both the characteristics and transmission of sound the students' ideas were elicited on the: prior questions ("Sound: What You Know!" worksheet); midpoint sound test; and the final questions ("Sound and Hearing Summary Questions"). For the reception of sound the students' ideas were elicited on the: prior questions ("Sound: What You Know!" worksheet administered at the start of the unit on sound and hearing); ear design assignment (administered following the unit on sound, but before the unit on the ear and hearing); the midpoint ear quiz (administered following the unit on the ear and hearing); and the final questions ("Sound and

Hearing Summary Questions") administered two weeks after the conclusion of the unit on sound and hearing).

3.07 Field Procedures, Data Collection and Recording

Throughout the unit on sound the selected students were given the same assignments, tests, projects and worksheets as other class members. Following each assignment, where necessary, I conducted informal interviews to clarify students' conceptualizations to assure my correct interpretations of what they meant. I made notes about these informal interviews directly on the students' test or assignment, writing students' responses verbatim in an effort to avoid distortion of the data. All tests, quizzes, and worksheets were collected and retained. I also wrote information from the informal interviews with the students directly on the students' assignments and tests.

3.08 Data Processing and Analysis

The initial phase of data processing involved transcribing the students' responses into a *question template*. A question template was created for each main sound topic: 1) characteristics of sound; 2) transmission of sound; and 3) reception of sound. These templates had questions on sub-topics from the worksheets, tests and assignments. Each student's answers were entered on the question template. The students responses were then compared with the "expected outcomes," providing the basis for how the students' conceptualizations were categorized. The term "expected outcomes" refers to the intended outcomes for student learning, that is the ideas that students were expected to develop as they moved through the units on sound and the ear's anatomy and physiology. For the list of "expected outcomes" refer to the following tables: Table 3.1 (the characteristics of sound); Table 3.2 (the transmission of sound); and Table 3.3 (the reception of sound).

Osborne and Freyberg (1985) categorized the possible effects on students' prior ideas of teacher-student interactions. They suggested five outcomes: 1) the undisturbed children's science outcome; 2) the two-perspective outcome; 3) the reinforced outcome; 4) the confused outcome; and 5) the unified scientific outcome. Although my study is not concerned solely with the students' conceptualizations at the end of the unit, the outcomes given by Osborne and Freyberg provided a framework for characterizing the students' conceptualizations at various stages, before, during and following the unit on sound.

Osborne and Freyberg's characterizations were modified to a *scientific* conceptualization, an incomplete conceptualization, and a confused conceptualization. The term *scientific* conceptualization was used to describe a student's ideas that matched the ideas listed on the "expected outcomes." (The term *scientific perspective* is also used in the analysis and refers to what I expected the students to know following instruction in science classs.) The term *incomplete* conceptualization was used to describe a student's ideas that matched the ideas listed on the "expected outcomes," but lacked at least one major concept. The term *confused* conceptualization was used to describe a student's ideas that did not match the ideas listed on the "expected outcomes." The term *conceptualization* was used in place of the term outcome because I was tracking the students' conceptualizations throughout the study, rather than seeking an end product.

The process of analyzing the data began by listing the expectations of what the grade 8 students should know about sound at the conclusion of the unit. The students' answers were documented for each stage of the study, on the prior questions, midpoint questions and final questions. The students' answers were compared with the "expected outcomes" and the students' ideas about each sub-topic was classified as either a *scientific* conceptualization, an incomplete conceptualization or a confused conceptualization. For each sub-topic the reasons for a particular classification of a students ideas was reported. These steps provided the preliminary basis for analysis of the the students' conceptualizations and are reported in the appendix. Following the initial analysis, certain themes emerged with respect to how the students' ideas evolved. The changes in or maintenance of students' ideas over the course of the study were characterized as types of *sonic journeys*. Finally, Gunstone's summary of the findings of research involving science students' conceptualizations was used as a framework for comparing the selected students' conceptualizations of the different sound-related topics. In sum, each selected student's ideas were investigated separately before comparisons were made between the selected students' conceptualizations.

3.09 Units on Sound and Hearing -- student experiments and teacher demonstrations

In Chapter IV the students' conceptualizations of sound are presented and analyzed. Details of the lessons are provided in the appendix. However, the students frequently cited the activities and teacher demonstrations performed during the units on sound and hearing in their answers to questions. For the purpose of clarification, the "Frequency Lab" and teacher demonstrations will be described in terms of what they involved and what they were intended to teach the students.

Early in the unit on sound, the students conducted an experiment entitled the "Frequency Lab." The students investigated three factors (length, mass, and distance pulled to the side) which could affect the frequency at which a pendulum vibrates. They were to use the information they gathered to design a pendulum that vibrated at a frequency of 1 Hertz. A pendulum was selected because it vibrates slowly enough to allow each vibration to be counted. The students were expected to learn that a pendulum's length affects its frequency of vibration, that a short pendulum vibrates at a higher frequency than a long pendulum. Further the students were expected to transfer these findings to other situations involving devices which make sound (particularly musical instruments), recognizing for example, that the shorter strings on a harp would vibrate at a higher frequencies, producing higher pitched sounds.

There were many teacher demonstrations conducted during the unit on sound and hearing. Following the "Frequency Lab," the students were instructed about the frequency ranges: infrasonic, audible, and ultrasonic sounds. An audiogenerator was used to produce sounds of frequencies in the audible and ultrasonic ranges. Unfortunately, the audiogenerator was not able to produce infrasonic sounds, but the students were instructed that infrasonic sounds are too low pitched to be heard. The students were provided with examples and uses of ultrasonic and infrasonic sounds.

As an introduction to sound transmission, a slinky (a long, coiled spring) was used to show the differences between a compressional wave (in which the coils vibrate in a direction parallel to the wave) and a transverse wave (in which the coils vibrate at right angles to the direction of the wave). The students were informed that sounds travel as compressional waves because vibrations cause regions of a medium to form alternately compressions (regions in which particles are close together) and rarefactions (regions in which particles are spread apart).

The next demonstration related to sound transmission involved a ripple tank. A ripple tank consists of a tray of water supported on legs above a table. Light is shone from above the tray through the water to a screen lying flat on the table. The light projects images of the water waves generated in the tray. The ripple tank is used to demonstrate that: 1) waves spread out in all directions; 2) waves bend around objects that they pass object; 3) waves rebound off objects they strike; 4) waves can pass through each other. The students were expected to transfer these properties of water waves in a ripple tank to the behaviour of sound waves. They were expected to learn: 1) that sound waves spread out in all directions and that the loudness decreases as the waves cover a greater region; 2) that sounds can travel around corners because sound waves can bend around and bounce off objects; and 3) that sound waves can pass through each other.

To illustrate that sound cannot pass through a vacuum because sound transmission requires particle collisions, a balloon was punctured in a bell jar resting on a vacuum pump. As the air in the bell jar was evacuated, the balloon expanded until it ruptured. Little or no noise was heard. A second balloon was punctured in the classroom (outside the bell jar) and the loudness was compared to that of the balloon popped in the vacuum. The explanation provided for the difference in loudness between the punctured balloons was that sound cannot pass through a vacuum and that the bell jar limited sound transmission.

An oscilloscope was used to provide visual representations of sounds of different pitch and loudness and also to compare the sounds produced by talking, singing, playing a musical instrument and sanding wood. The students were expected to learn that the wavelength (distance between consecutive peaks) corresponded to a sound's frequency and that the shorter the wavelength, the higher the pitch of the sound represented. They were also expected to learn that the amplitude (peak height) corresponded to a sound's intensity (loudness), that the greater the amplitude, the greater the loudness.

During the unit on the ear and hearing, the audiogenerator was used again to produce sounds ranging from 20 Hertz to 100 000 Hertz to allow the students to determine their audible ranges (i.e. the frequencies they can hear). The students were informed that the longest of the tiny *hairs* in their cochleas determined the lowest pitched sound they could hear and that the shortest of the tiny *hairs* in their cochleas determined the highest pitched sound they could hear.

In Chapter IV, following the presentation of the students' conceptualizations, much of the analysis of the students' conceptualizations focused on whether what the students learned from the experiments and teacher demonstrations was what the teacher had intended. The experiments and teacher demonstrations provided representations of a variety of sound properties, many of which cannot be observed directly. For example, we cannot see sound waves, but by studying water waves to learn about the properties of waves, some of the information can be applied to the behaviour of sound waves. The analysis of the students' conceptualizations centred on how the "Frequency Lab" and teacher demonstrations influenced the students' ideas about sound and hearing.

3.10 Description of Terms

In the analysis of the students' data certain terms were used to clarify both the times and how data were gathered. The term *prior questions* refers to questions the students answered related to sound (on the "Sound: What You Know!" sheet) the period before instruction about sound and hearing commenced. The term *midpoint test* refers to the sound test administered following the unit on the characteristics and transmission of sound. The *midpoint quiz* refers to the ear quiz administered following the unit on the ear and hearing. The term *final questions* refers to questions the students answered two weeks after the unit on sound and hearing concluded (on the "Sound and Hearing Summary Questions" sheets). In reporting the students' responses the term *on clarification* was used to note that the information had been gathered during informal interviews with the students. The purpose of the clarification was to ensure that my interpretations of the students' responses were as the students intended. The term *during probing* referred to situations during the interviews in which I asked the students to provide more detail than their written answers or diagrams gave. Throughout the remaining chapters, the unit on *sound* is also referred to as the unit on *the characteristics and transmission of sound.* The unit on *hearing* is also referred to as the unit on *the ear's anatomy and physiology*, as well as the unit on the *reception of sound.*

3.11 Methodological Assumptions

A major assumption was that the lessons of the unit on sound and hearing were logically arranged and at an appropriate level for the students. This assumption was believed to be reasonable, as this unit on sound and hearing was developed and modified over the course of five years of teaching Science 8. Another assumption was that the students would do their best to provide their conceptualizations honestly. Within the study, there was no advantage to the student to be dishonest. In fact, the students seemed to enjoy exploring their own conceptualizations and having their ideas treated with interest and respect so I assumed that the students presented to the best of their understanding what they knew and understood.

3.12 Limitations

A potential limitation of this study is that only students who were likely to complete the activities of the study were selected. None of the selected students failed either of the first two terms in this course. This is not necessarily a limitation, in the sense that this study does not attempt to produce statistically generalizable information, covering every possible learner. Rather it is a reflective study which explored the process by which four students generated knowledge, and is presented as such. My role as teacher-investigator created problems. As a researcher, I was interested in the students' conceptualizations. As a teacher I was responsible for facilitating learning and assisting the students. In designing this study, I took care to separate the research and evaluation. I wanted to provide the students with ample time and assistance from me as the teacher, and limited my role as researcher to those times indicated on the schedule. Further, only the midpoint sound test and midpoint ear quiz counted for marks in the traditional style of *right* or *wrong* answers.

<u>Frequency and Pitch</u>

• <u>Frequency</u>
  - for sound, frequency refers to the rate of vibration
  - the purpose of the frequency lab was to investigate how the length of a string affected the frequency of a pendulum / a pendulum was chosen because it vibrates slowly enough to allow the vibrations to be counted and the frequency calculated

• <u>Pitch</u>
  - for sound, pitch describes the frequency of a sound, but not the loudness (as the frequency increases, so does the pitch and vice versa)
  - the pitch of a stringed instrument can be increased by shortening or tightening the string
  - the pitch of a wind instrument can be increased by shortening the length of the air column (by opening some holes or valves)
  - for the cochlea of an ear, the short hairs detect higher-pitched sounds and the long hairs detect lower-pitched sounds

<u>Frequency Ranges</u>

• <u>Ultrasonic Sounds</u>
  - frequencies greater than 20 000 Hz and too high for humans to hear
  - used in echolocation (sonar); kidney stone crushers; ultrasound for giving a picture of a developing fetus in a pregnant woman; ultrasonic cleaners (for glassware); on trucks to scare deer off the highway; dog whistles

• <u>Audible Sounds</u>
  - approximately 20 Hz to 20 000 Hz
  - different animals have different audible ranges (depends on the lengths of the hairs in the cochlea)

• <u>Infrasonic Sounds</u>
  - frequencies less than 20 Hz and too low for humans to hear e.g. earthquakes, underground explosions

<u>Table 3.1</u> Characteristics of Sound: Expected Student Outcomes

Particle Collisions
- sounds are produced by objects that vibrate
- sound requires particles (i.e. a medium) to pass through)
- the vibrations create a compressional wave that forces particles to squeeze together (compressions) and spread apart (rarefactions) in a repeating cycle
- sound travels as a chain reaction of collisions between particles (and is similar to heat conduction)
- the particles do not travel with the sound from the source to the listener, but vibrate in one area
- sound particles do not exist
- sound spreads out in all directions

States of Matter
- sound can pass through all states of matter (solids, liquids, gases)
- sound changes speed depending upon what it is passing through
- sound generally travels fastest through solids because the particles are closest together (i.e. a faster chain reaction can be created)
- sound generally travels slowest through gases because the particles are farthest apart (i.e. a slower chain reaction is created)
- sound cannot pass through a vacuum because there are no particles available to vibrate in a vacuum

Speed of Sound Compared to Light
- sound travels much slower than light
- sound --> 340 m/s
- light --> 300 000 km/s
- lightning is seen before thunder is heard because light travels much faster than sound
- light takes virtually no time to cover distances of a few kilometres, but sound takes approximately 3 seconds per kilometre / this difference can allow experiments to be devised to measure the speed of sound

Waves
- sound travels as a wave
- sound travels as a compressional wave (series of compressions and rarefactions)
- sound does not travel as a transverse wave (water wave)
- sound waves travel outwards from the source in all directions and lose energy as they spread out and become quieter
- waves can bend around objects
- waves can reflect off objects creating echoes
- sound waves can travel around corners by bending or reflecting
- oscilloscope provides a representation of sound waves (looks like a transverse wave)
  - peak height corresponds to loudness
  - wavelength (distance between peaks) corresponds to frequency and pitch
  - the shorter the wavelength the higher the pitch

Echoes
- echoes are rebounded sounds
- echoes are quieter than the original sound because some of the energy is absorbed by the object the sound hit, and the sound energy is spread out so only a small amount returns to the source
- echolocation involves a sound being sent out and reflecting back to the source / based on the time it took the sound to hit an object and return, the object's location can be calculated
- sonar is an example of echolocation

Table 3.2 Transmission of Sound: Expected Student Outcomes

<u>The Ear: Structure and Function</u>
• structures: label and sketch diagrams
• function:
• <u>Outer Ear</u>
  - ear flap: collect sound and direct sound through ear canal to eardrum
  - eardrum: vibrate in response to sound and transmit vibrations to middle ear
• <u>Middle Ear</u>
  - ossicles (hammer, anvil, stirrup) vibrate in response to eardrum
    - amplify sound and transmit sound to oval window of cochlea
• <u>Inner Ear</u> (fluid-filled cochlea)
  - cochlea: oval window much smaller than eardrum (thus the sound is more concentrated and amplified)
  - tiny "hairs" in the cochlea respond to different-pitched sounds
  - the short hairs detect higher-pitched sounds and the long hairs detect lower-pitched sounds
  - tiny hairs attached to auditory nerve

• <u>Auditory Nerve</u>
  - transmits nerve impulse to brain
  - brain *makes sense* of the information
• semicircular canals --> sense of balance (unrelated to hearing)
• eustachian tube connects middle ear to throat

<u>Hearing Loss / Deafness</u>
• main cause of hearing loss is loud sounds (damage hairs of cochlea)
• other causes of hearing loss:
  - ear canal obstructed by objectes (e.g. eraser, gum, or ear wax)
  - eardrum punctured or damaged by poking
  - eardrum punctured or damaged by rapid pressure changes (e.g. scuba diving)
  - infections (can travel from throat through the eustachian tube to the middle ear)
  - birth defects (e.g. no ear flap; damage to auditory nerve)
• conductive hearing loss (usually affects outer or middle ear)
  - a blockage or obstruction such as ear wax
  - often can still hear (muffled)
  - loss usually can be corrected
• nerve damage
  - damage to the hairs in the cochlea or the auditory nerve is usually permanent
  - can end up with partial or total hearing loss

<u>Table 3.3</u> Reception of Sound: Expected Student Outcomes

CHAPTER IV

THE STUDENTS' SONIC JOURNEYS (CONCEPTUAL CHANGES)

4.1 Introduction to the Students' Sonic Journeys

In this chapter the changes in each of the four students' conceptualizations of sound and the ear's anatomy and physiology are presented as *sonic journeys*. The students' conceptualizations of all the sound and hearing topics on the prior, midpoint, and final questions were chronicled and categorized in the preliminary analysis (as an example, analysis of Bill's conceptualizations is found in Appendix 4). To organize the presentation of the preliminary analysis the changes in the students' conceptualizations are characterized as types of sonic journeys. Based on the categorizations, the four student's conceptualizations are characterized as different types of sonic journeys: 1) Bill's journeys are presented as *Riding Buses;* 2) Mary's journeys are presented as *Orienteering Without a Compass;* 3) Frank's journeys are presented as *Drag Races;* and 4) Jane's journeys are presented as *Highways and Byways.* The sonic journeys do not attempt to explain **how** each student learned. Rather, the journeys provide metaphors which represent the ease or difficulty each student **appeared** to experience while learning about sound and hearing.

Not all of the preliminary analysis will be included in each student's *sonic journeys.* Instead, the changes in each student's conceptualization for particular sub-topics of sound and hearing which are represented by the student's *sonic journeys* will be presented. This means that between students there will be differences in the sub-topics of sound and hearing which are focused on and the order in which the sub-topics are presented.

Prior to describing each student's sonic journeys a chart provides a graphic summary of the students' conceptualizations for the characteristics, transmission, and reception of sound. Following analysis of each student's conceptualizations of sound and hearing individually, comparisons between the students are made using Gunstone's summary of findings as a framework.

Characteristics of Sound

	Prior Questions		Mid-point Sound Test		Final Questions
Frequency and Pitch	Δ	-->	Δ	-->	Δ
Frequency Ranges	Δ	-->	O	-->	O

Transmission of Sound

	Prior Questions		Mid-point Sound Test		Final Questions
Particle Collisions	Δ	-->	□	-->	Δ
States of Matter	Δ	-->	O	-->	O
Waves	Δ	-->	Δ	-->	Δ
Echoes	Δ	-->	O	-->	O
Sound vs. Light	O	-->	O	-->	□

Reception of Sound -- The Ear: Structure and Function

	Prior Questions		Ear Diagram		Mid-point Ear Quiz		Final Questions
The Ear's Anatomy	Δ	-->	Δ	-->	O	-->	O
The Ear's Physiology	Δ	-->	Δ	-->	Δ	-->	Δ
Hearing Loss / Deafness	Δ	----------------		-->	O	-->	Δ

Δ = confused conceptualization

□ = incomplete conceptualization

O = *scientific* conceptualization

\- = no conceptualization (student provided no information about a particular concept)

Table 4.1: Bill's Sonic Journeys

4.2 Bill's Journeys: Riding Buses

4.2.1 Bill's Background

In science class Bill earned a high "B" in the first term and a "C+" in the second. His average score on tests in the first term was 80% which was similar to his first term science mark of 82%. In the second term his overall mark was 68% and his average score on tests was 67%. Bill was a cooperative student who enjoyed working and learning, but he was not easily satisfied with his work. I selected him because he would complete all the activities making up this study. He had difficulties in writing, particularly spelling and grammar, but packed his answers with sufficient information to create a context which made his answers understandable.

4.2.2 Introduction to Bill's Journeys

In representing Bill's journey, *scientific* conceptualizations of each sound topic were characterized as buses with Bill as a passenger. Metaphorically, Bill attempted to catch each bus. Over the course of the study, Bill's conceptualizations of sound changed in four distinct patterns. He had either: 1) a *scientific* conceptualization throughout the study (meaning he boarded the bus by the time of the prior questions and remained through the midpoint test and the final questions); 2) a confused conceptualization on the prior questions followed by a *scientific* conceptualization for the remainder of the study (meaning he boarded the bus on the midpoint questions and remained through the final questions); 3) confused conceptualizations on the prior questions and final questions, but a *scientific* conceptualization on the midpoint test (meaning he boarded the bus for only the midpoint questions and disembarked before the final questions); or 4) confused conceptualizations throughout the study (he never caught the bus). For the *reception of sound* Bill took a combined journey of #2 for the ear's anatomy and #3 for the ear's physiology. Although Bill was an eager learner, he was inconsistent. Overall, Bill's conceptualizations developed in a wide range of patterns.

4.2.3 Bill rides the whole trip

4.2.3.1 Transmission of Sound -- the speed of sound versus the speed of light

On the prior questions Bill said that light travelled faster than sound "because it could take a while for sound to reach your ear from a distance but light can get to your eyes from a distance." During probing, he said "light can travel farther than sound because light comes from stars that are a long distance away, but sounds cannot go that far."

On the midpoint sound test Bill said that sound travelled at 340 m/s. He explained that lightning is seen before thunder is heard because "light moves way faster at 300 000 km/s than sound at 340 m/s."

On the final questions Bill's explanation for why an airplane appeared to be ahead of the sound it made was that the airplane broke the sound barrier. On clarification, he explained that the airplane moved faster than the speed of sound creating a sonic boom. He added that he had heard sonic booms produced by airplanes at an air show. When I asked him whether all airplanes appeared to be ahead of the sound they made, he said, "no, only those that go faster than the speed of sound." During probing I asked him about the speeds of sound and light. He said that light travelled faster than sound. Although asked to design an experiment to determine the speed of sound, Bill did not. Instead he listed an algebraic formula that related speed, distance and time. On clarification, he said that even though he knew how to calculate the speed of sound, sound went too fast to measure.

On the prior questions Bill had a *scientific* conceptualization of the relative speeds of sound and light. He knew that light travelled faster than sound which fit the *scientific* perspective. Based on his observation that he could see stars that were great distances from the earth, he thought that light could travel farther than sound.

On the midpoint sound test Bill had a *scientific* conceptualization of the relative speeds of sound and light. He applied the information about the relative speeds of sound and light to explain why lightning was seen before the accompanying thunder was heard. Not only did he know that light travelled faster than sound, he listed their respective speeds correctly.

On the final questions Bill had an incomplete conceptualization of the relative speeds of sound and light. For the question of why an airplane appeared to be ahead of the sound it made, he focused on the relative speeds of sound and the airplane rather than the relative speeds of sound and light. Although his answer was not wrong, it was only when questioned directly about the relative speeds of sound and light that Bill stated that light travelled faster than sound. He said that sound took time to travel a distance and during that time the plane was moving forward. He thought that the airplane was travelling faster than the speed of sound so the airplane was ahead of the sound.

4.2.4 Bill boards in the middle and stays on

4.2.4.1 Characteristics of Sound -- frequency ranges

On the prior questions Bill said that ultrasonic sound was "sound that moves so fast that we can't hear it." On clarification, he said ultrasonic sounds travelled too fast to be heard. He said that ultrasonic sounds could be "used to look at a baby in a mother's stomach" (i.e. a developing fetus in a pregnant woman). During probing, he said that he had not heard of the term infrasonic sound.

On the multiple choice section of the midpoint sound test he correctly answered that: infrasonic sounds are "too low to be heard by humans"; a "bat" uses echolocation to fly and hunt in the dark; and that earthquake waves are an example of "infrasonic sound." As examples of uses of ultrasonic sounds he listed, "pregnancy baby checkers [referring to checking the fetus of a pregnant woman], kidney stone crushers, and a dog whistle." He described echolocation and identified it as a use of ultrasonic sound as in sonar. He said the frequencies he could hear were from 20 Hz to 20 000 Hz. In his sketch of an uncoiled cochlea Bill drew tiny hairs of different lengths and he indicated incorrectly that the long hairs detected high pitched sounds and the short hairs detected low pitched sounds.

On the final questions Bill said that ultrasonic meant "sounds so high we can't hear them." He said the sounds he could hear were from 20 Hz to 20 000 Hz. He knew that that the cochlea had tiny hairs that detected pitch and frequency and explained that the short hairs of the cochlea detected high pitched sounds. Bill said that sonar "can be used to find were [where] sunken boats are or treasure" and involved "sending out a sound wave and seeing how long it takes to get back." As examples of uses of ultrasonic sounds, he listed "pregnant woman checkers, dog whistles, and kidney stone crushers."

On the prior questions Bill had a confused conceptualization of the frequency ranges. He was aware of the term ultrasonic sound and gave a correct use, but incorrectly thought that ultrasonic sounds were so named because they travelled faster than other sounds. He did not know of the infrasonic sound range or that ultrasonic sounds cannot be heard by humans.

On the midpoint sound test Bill had a *scientific* conceptualization of infrasonic, audible, and ultrasonic frequency ranges. He correctly identified a definition, an example of infrasonic sound, and gave three correct applications of ultrasonic sounds. He correctly listed the frequencies that humans can typically hear.

On the final questions Bill had a *scientific* conceptualization of frequency ranges. He listed the same examples of uses of ultrasonic sounds that he listed on the midpoint sound test and he correctly defined his audible range as 20 Hz to 20 000 Hz.

4.2.4.2 Transmission of Sound -- via particle collisions and through the states of matter

Bill did not select one of the descriptions of sound transmission provided on the prior questions (like a baseball being thrown from one place to another; like the form of heat transfer called conduction; like the form of heat transfer called convection; like sunlight passing from the sun to earth; or something else). Instead, Bill provided his own idea, that sound travelled "like hitting a gong on one side of a room and a gong on the other side of the room vibrates." On clarification, he could not explain how the vibrations passed from one side of the room to the other, but he said that "somehow the gong making the sound caused the gong on the other side of the room to vibrate." His description of how the sound of a bat hitting a ball travelled was that the sound "bounced off the bat and bounced around until it got to your ear." In his sketch of how the sound of howling wolves travelled to a tent he drew wavy lines (labelled sound waves) and said that the sound waves rebounded off trees until they arrived at the tent. During probing he said that sound travelled in waves that spread out from the source of the noise. When asked whether sound could travel through all states of matter, Bill answered, "yes, because for all states [of matter] you can hear sound." He added that you can hear sound "underwater, in a room and in the air." He said it was possible to hear underwater because sound passed through water. Although Bill said that sound could pass through all states of matter, he did not think that sound could pass through a solid wall "because the sound waves bounce off the solid wall" and produce an echo. He said that sound could not pass through a vacuum because it (the sound) had nothing to bounce off. He thought that the speed of sound was a constant.

On the midpoint sound test Bill said that heat conduction was similar to sound transmission because they "both occur in all states of matter and they both occur fastest in solids because in solids the particles are locked together." For the scene in which a spaceship was hit by a missile he thought the sound of the explosion was heard shortly after because light travelled faster than sound. He said that it was possible to hear sounds underwater because sound did not travel in the form of *sound particles* and could go through a liquid. On the midpoint sound test it was suggested that sound should pass through gases the fastest and solids the slowest, the reverse of what is observed in nature. Bill said that the explanation accounted for how the speed of sound changed in solids, liquids, and gases. He said "sound travels fastest in solids and we move the slowest in solids so it all matches up." In describing himself as an air particle in a room with a sound passing through, Bill said he would start to vibrate, bump into another student and she would vibrate and bump into another student and so on. Bill was asked to sketch, label, and describe how the sound of a loud car reached him in a classroom when the window was open, and then when the window was closed. For the car's sound entering a classroom through an open window he drew circles that increased in size, labelled them "sound waves," and said that they came from the car. These waves passed through the open window and spread out in the classroom. He said the sound of the engine would pass through an open window to his ear. He also drew circular lines (representing sound waves) rebounding off the wall next to the window. For the situation with a closed window Bill drew sound waves bouncing off the wall, but he also showed the particles comprising the wall vibrating and said that "some of it [the sound]" would "seep through [the wall] to your ear." He sketched particles vibrating within the wall, and drew smaller waves (to represent quieter sounds) passing to the listener. Bill's evidence that sound did not travel in the form of *sound particles* was based on the vacuum pump demonstration in which a balloon was burst in a bell jar under vacuum conditions and did not produce an audible sound. He said, "we could not hear the balloon nearly as well as when it was outside the vacuum."

On the final questions, comparing heat conduction to sound transmission, Bill said that both passed fastest through solids because solids' particles were *locked together*. On clarification, he said that in a solid the particles were closer together than in a gas so if one particle moved it would collide sooner with a neighbouring particle. He also thought that sound transmission was "like light because sound can bounce off stuff." He said that sound would not be heard if an asteroid hit the moon because there were no air particles for the sound to travel through. He said that the rocks would make a sound when banged underwater "because sound can travel through water particles." Bill said that if your ear became plugged with chewing gum "you would not be completely deaf because the sound could slowly travel through the gum." On the final questions Bill faced a problem about the transmission of sound presented by three diagrams showing how sound would travel through a solid, a liquid, and a gas. It was suggested that sound should travel fastest through gases because there were large enough gaps between the particles to allow sound to pass through easily and that sound could not pass through a solid because the particles were *locked together* without any gaps to allow the sound to pass though. Bill said the theory was incorrect because sound travelled fastest through solids. On clarification he said "sound needs particles, not gaps so the theory is completely backwards."

He did not think that *sound particles* existed. He said that if *sound particles* existed they should be able to travel through empty space, but he knew that sound could not pass through a vacuum. Bill thought that collisions between neighbouring particles allowed sound to travel through the three states of matter. In his diagram of sound transmission from a tuning fork Bill drew dots representing air particles to the right of the tuning fork. He labelled the dots that were close together "compressions," and the dots that were far apart "rarefactions." For the diagram of the motorcycle's noise entering a restaurant, he sketched a motorcycle and dots (representing air particles) in the restaurant. He provided few details of how the sound travelled, stating that the particles vibrated and collided with their neighbours to carry the sound. He did not draw sound waves or include waves in his description of how the sound passed into the restaurant.

On the prior questions Bill had a confused conceptualization of sound transmission. He knew that sounds were produced by objects that vibrated and that sound travelled in the form of waves. He could not explain how sound waves travelled, and because he did not realize that particles were required for sound transmission, he could not describe the effect of a sound wave on particles as the sound passed. He thought that sound could travel only in straight lines without bending, but his description of sound transmission was unclear. The main feature in his sketch of the howling wolves was sound waves rebounding off trees until they reached a camper in a tent. Bill had a confused conceptualization of how sound passed through the states of matter. He did not know that sound transmission required particle collisions and that the different arrangements of particles in solids, liquids, and gases influenced the speed of sound through each state. Initially, Bill stated that sound could pass through solids, liquids, and gases, but on a separate question he contradicted himself when he said that sound could not pass through a solid because the sound would just bounce off. He thought incorrectly that sound could travel at only one speed. He said correctly that sound could not pass through a vacuum, but his reason was incorrect. He said that there was nothing for the sound to bounce off in a vacuum, rather than that a vacuum lacked particles which were needed for sound transmission. Bill knew that sources of sound vibrated, that sound travelled in the form of waves and could rebound off objects and what sound could and could not pass through, but he was unable to describe and explain sound transmission in terms of of particle collisions and compressional waves.

On the midpoint sound test Bill had an incomplete conceptualization of sound transmission. While he retained his earlier ideas that sources of sound vibrated and that sound travelled in the form of waves, he also explained that a sound source created compressional waves which caused particles to collide with neighbouring particles. He knew that sound transmission was similar to heat conduction and that while the sound moved away from the source, the particles themselves did not travel with the sound. Bill argued correctly against the idea of *sound particles*, special particles that carried sound. He based his argument on the vacuum pump demonstration, that if *sound particles* existed they would pass through a vacuum. Bill described what happened to particles during sound transmission. Although he said that sound travelled in the form of a compressional wave, his conceptualization of sound transmission was incomplete. Bill did not represent compressions and rarefactions in his diagrams of sound transmission or explain how compressions and rarefactions were produced.

Bill had a *scientific* conceptualization of how the states of matter affected sound transmission. He described the role of particles in sound transmission. He explained how the arrangement of the particles in solids, liquids, and gases affected the speed of sound through each state of matter. Bill knew that sound passed fastest through solids and slowest through gases. He explained correctly that sound passed fastest through solids because the particles were close together so the series of collisions between particles occurred rapidly. Bill said that sound could not pass through a vacuum because there were no particles to vibrate. Bill was asked "*In the Star Wars series of movies you would often see a spaceship struck by a missile, and shortly after you would hear the explosion. What is wrong with this scene?*" The intent of the question was to probe whether Bill understood that sound could not travel through a vacuum (in this case outer space). Bill thought the question was asking him about the relative speeds of sound and light and therefore there was nothing wrong with hearing the explosion after seeing it because light travels faster than sound. When faced with the idea that sound should travel like a person walking and thus pass through gases the fastest and solids the slowest Bill thought incorrectly that the explanation described how the speed of sound changed in solids, liquids and gases.

On the final questions Bill had an incomplete conceptualization of sound transmission. He stated correctly that sources of sound vibrated and created compressional waves. In his diagram of sound travelling from a tuning fork he included alternating regions labelled compressions and rarefactions. He knew that sound transmission was similar to heat conduction, but he also thought that sound travelled like light. He argued against the idea of *sound particles* on the basis that if *sound particles* existed sound should have been able to pass through a vacuum. His description of sound transmission was limited to the "particles are vibrated," but he knew that the particles stayed in one area and did not travel with the sound. Bill had a *scientific* conceptualization of sound transmission through the states of matter. He knew that sound could travel through solids, liquids, gases, and not through a vacuum. He argued that sound would not be heard on the moon because the moon had no atmosphere (particles) for the sound to pass through. He answered correctly that the sound of two rocks banging underwater could be heard because the vibrations could pass through both the particles comprising tthe water and the air above. Bill knew that sound could pass through solids so it was unlikely that he would become completely deaf in an ear that was plugged by chewing gum.

4.2.4.3 Transmission of Sound -- echoes

On the prior questions Bill said that sound could travel only in straight lines and not around corners. On clarification he said that "sound cannot bend around corners and the only way sound could get around a corner was if it bounced off something." He said that echoes occurred when "the sound you make bounces off say mountains and back to your ears." He provided no reason for why echoes were quieter than the original sound.

On the midpoint sound test Bill said that one way for sound to travel around corners was to "pinball [bounce] off the walls" and another way was it could "bend around corners." On clarification, he said that the term "pinball" meant bounce, so the sound could bounce off the walls to get around a corner. He added that during the ripple tank demonstration he had observed waves bending around corners, and since sound was a wave, sound should bend as well. Bill said that "the echo occurs by your sound waves rebounding off the rock walls and back to your ears." He explained that the echo was quieter "because the wall absorbs some of the energy and because the energy is more spread out." He said that echolocation is "when something makes a noise and you see how long it takes to travel back to it." He added that we use echolocation for "stuff like sonar."

On the final questions he said that even when you cannot see the source of the sound, "sound can travel long distances but it also can bend around corners or ping pong [bounce] off things" to reach you. He said that echoes were sound waves that bounced off solids and echoes were quieter than the original sound because the object absorbed some of the energy and the sound is more spread out. He said sonar involved sending out a sound wave and seeing how long it took to get back. He added that sonar could be used to find where boats or treasure were.

On the prior questions Bill's conceptualization of echoes was incomplete. He knew sound could travel around corners by bouncing off other walls. Echoes were a significant component of his description of sound transmission. Bill's ideas about echoes did not account for why an echo was quieter than the original sound. He did not have a clear understanding of sound transmission and could not describe the details of what happened when a sound rebounded off an object. Thus it was not logical to categorize his conceptualization of echoes as fitting a *scientific* perspective.

On the midpoint sound test Bill had a *scientific* conceptualization of echoes. He explained how they occurred and applied his ideas to explain how sound could travel around corners and be used in echolocation. The major change in his conceptualization of echoes was his ability to explain why an echo was quieter than the original sound. Based on the ripple tank demonstration he recalled that the waves had spread out by the time they returned to the source. He said that the energy had spread out. He also said that some of the sound's energy was absorbed by the wall indicating that he recalled our discussion of energy transformations several units prior to our investigation of sound. Bill described the process of echolocation, emphasizing that the total time of the sound's round trip was used to calculate how far away an object was. He knew that sonar was an example of echolocation.

On the final questions Bill had a *scientific* conceptualization of echoes. His answers were similar to those on the midpoint sound test and he explained how echoes occurred, what echolocation was used for and how it worked. He also provided two correct reasons for why an echo was quieter than the original sound. His description of sonar was detailed as he outlined what sonar involved and was used for.

4.2.5 Bill takes a short ride in the middle and disembarks early

4.2.5.1 Reception of Sound -- causes of deafness

On the prior questions Bill said that our sense of hearing was vital to us because "you have to hear eighteen wheelers [large semi-trailer trucks] coming down the highway so you don't get hit" because you could hear the trucks in advance. He said loud noises such as those produced by airplanes were a cause of deafness. He added that loud sounds could "blow your eardrum." He thought the chief reason to learn about sound and hearing was to protect our sense of hearing.

On the midpoint ear quiz Bill said the main cause of hearing damage was loud noises which levelled the tiny hairs in the cochlea and could not be fixed. He said that puncturing or damaging the eardrum was a major cause of hearing loss, but that the eardrum could repair itself. To explain how changes in altitude affected hearing, he said "your eardrum bends inward when we go low down and outward when you go upward." During probing, he explained that when the pressure inside and outside the ear was not balanced, the eardrum was pushed either in or out. He said a throat infection could cause hearing loss because it could "creep up the eustation [eustachian] tube and . . . severely damage the ossicals [ossicles]."

On the final questions Bill said that if your ear became plugged with gum, "you would not be completely deaf because the sound could slowly travel through the gum." When asked what would happen to his hearing if his ossicles separated from each other, Bill said "once there [they are] broken your [you're] deaf." As two different major causes of hearing loss he listed: a punctured eardrum, which he classified as temporary hearing loss; and "loud noise levelling your nerve endings in the cochlea" which he classified as permanent hearing loss.

On the prior questions Bill had a confused conceptualization of hearing loss and deafness. He correctly stated that loud sounds were the main cause of hearing loss, but incorrectly said that loud sounds damaged the eardrum (rather than the hairs of the cochlea). He did not list any other causes of hearing loss. Not surprisingly Bill was unable to explain how the ear was damaged because he had little knowledge of the ear's anatomy and physiology.

On the midpoint ear quiz Bill's conceptualization of hearing loss and deafness approached the *scientific* perspective. On the midpoint quiz, as on the prior questions he stated correctly that loud sounds were the leading cause of hearing loss and damaged the tiny hairs of the cochlea. He correctly identified other causes of hearing loss such as a punctured eardrum, or throat infections affecting the ossicles in the middle ear. He said that the eardrum could repair itself which is often the case. He successfully answered several other challenging questions. He explained how changes in altitude and air pressure affected the eardrum. He described how the eustachian tube connected the middle ear to the throat so that throat infections could reach the ossicles and damage the sense of hearing. The major omissions from Bill's discussion of hearing loss were that he did not categorize the damage to the cochlea as permanent and he did not list other causes of hearing loss such as birth defects, obstructions in the ear canal, and damage to the auditory nerve or the brain.

On the final questions Bill had a confused conceptualization of hearing loss and deafness. He correctly argued that if someone's ear canal became plugged with gum, the person would not be completely deaf because sound could still pass through the gum. For the situation of the damaged ossicles he said the hearing loss would be permanent and the person would be completely deaf. He did not realize that the sound might bypass the ossicles through the bones of the skull to reach the cochlea. He correctly thought that a punctured eardrum would likely cause temporary hearing loss and damage to the hairs in the cochlea would cause permanent hearing loss. He did not distinguish between conductive hearing loss and neural hearing loss.

4.2.6 Bill missed the bus

4.2.6.1 Characteristics of Sound -- frequency and pitch

On the prior questions Bill thought that all sources of sound travelled as waves and vibrated in peoples' ears or whatever they hit. He described the situation at a hockey game as the sound produced by "people's vocal cords [the sound produced by people] echoing off the walls of the stadium." He did not describe the sound produced by a mosquito. Bill said the pitch "tells us the deepness of the sound." In order to produce a higher pitched sound he said "change the setting on the amplifier." For the change in pitch of a siren as an ambulance approached he said the sound went from low to high and depended on how close the ambulance was. On clarification, he said that the sound became louder as the ambulance neared.

On the multiple choice section of the midpoint sound test Bill answered correctly that all sources of sound "vibrate," that long pipes made "lower notes," that frequency was measured in "hertz," and the frequency of an object " is the number of times it vibrates in one second." On the short answer section of the midpoint test Bill explained that as the frequency increased the pitch increased. To make a higher pitched sound with a guitar he suggested that "you could pluck the strings harder or shorten the strings with your fingers." To change the pitch of a drum he suggested hitting the drums harder. He defined the term *vibration* as "something moving back and forth." He said the purpose of the *frequency lab* was "to see if the length of something effects [affects] its sound," and concluded that "when you lengthen it [the pendulum] it [the sound] becomes louder."

On the final questions Bill described the relationship betwen pitch and frequency as the higher the frequency the higher the pitch, and the lower the frequency the lower the pitch. He explained that to increase the pitch of a note on the flute "you could blow harder or cover different holes." For the purpose of the frequency lab he said "we did the experiment to see if the length of the pendulum affected its sound waves." He added that by making the pendulum longer, the sound travelled farther. For the question of why the pitch increased as a drainpipe filled with water, Bill said that when the pipe was filled the sound was a lower pitch because the water muffled the sound, and when the pipe was empty the pitch was higher because the sound was not muffled.

On the prior questions Bill had a confused conceptualization of frequency. In his description of the sounds produced by a mosquito and a crowd in a stadium, he said that the sounds would echo, but he did not mention the terms loudness or pitch. On other questions he thought that the pitch of a sound described the sound's loudness. His confusion between pitch and loudness was demonstrated when he said an amplifier could be used to increase the pitch of a sound, and when he said the pitch of an approaching ambulance's siren became higher because the sound became louder.

On the midpoint sound test Bill had a confused conceptualization of frequency. At times it appeared that he understood the concept of frequency. He correctly defined the terms frequency and vibration and knew that the frequency of a sound determined the pitch. He knew that long pipes on an organ made lower notes and he described the purpose of the frequency lab correctly. There were inconsistencies in his conceptualization of frequency. He thought that the length of a pendulum affected loudness rather than frequency. This was an interesting conclusion, because it was unlikely that the pendulum produced an audible sound, and the lab was entitled "Frequency Lab." While he correctly stated that a higher pitched sound could be produced on a guitar by using a shorter string, he added incorrectly that plucking the strings harder would also increase the pitch. Plucking the strings harder should increase the loudness of the sound, not the pitch. Similarly, he said hitting the drums harder would increase the pitch of the sound, rather than the loudness of the sound. Bill could remember definitions of such terms as frequency and pitch, and how the length of an object (or musical instrument) affected the pitch of the sound it produced. However, he did not distinguish between the loudness and the pitch of a sound. He used the terms interchangeably.

On the final questions Bill had a confused conceptualization of frequency and pitch. He knew that pitch and frequency were related, and correctly explained that as the frequency increased the pitch increased, and as the frequency decreased the pitch decreased. In the *frequency lab* he thought that a longer string produced a stronger sound that could "travel farther." In his response to the question on why the pitch of sound increased as tapwater filled a drainpipe, Bill did not mention the change in pitch. Instead, he described changes in the loudness of the sound and related the lower pitched sound at the beginning to a "muffled" or quieter sound. Similarly, he linked the higher pitched sound to an "unmuffled" or louder sound. Bill did not distinguish between the pitch of a sound and the loudness of a sound. He associated low pitch with quiet sounds and high pitch with loud sounds. He used the terms pitch and loudness interchangeably which made it difficult for him to apply his conceptualization of frequency to situations that demanded more than memorizing definitions of vocabulary terms.

4.2.6.2 Transmission of Sound -- waves

On the prior questions Bill used the term *sound waves* several times. In one instance he said that sound could not travel through a solid wall because the sound waves bounced off the wall. In his diagram showing how the sound of howling wolves travelled through the air to the camper in the tent he also used the term sound waves. When asked what a sound wave was he said he wasn't sure, but he thought it might be something like a water wave.

On the midpoint sound test Bill correctly answered that in rarefactions the air particles were "spread out." He said the ripple tank demonstration provided evidence that sound travelled in the form of waves. Bill said he knew that sound travelled as a compressional wave because he could see the compressions when the slinky was wiggled. His sketch of how a quiet, high frequency sound would appear on an oscilloscope featured large peaks and troughs packed closely together which corresponded to how a loud, low freqency sound. He correctly selected the oscilloscope wave representations of the quietest sound and noise, but incorrectly selected the wave representing the quietest sound instead of the lowest pitched sound. He said that an oscilloscope gave a misleading representation of sound because "sound travels as a compressional wave [and] the oscilloscope shows it as a transverse wave. He said a firecracker sounded much louder when it was set off 1 metre away than 1 kilometre away because "sound travels in m/s [metres per second], not km/s [kilometres per second]." On clarification, he said sound would have more time to lose energy if it travelled 1 kilometre. In describing what would happen to him if he were an air particle and a sound was passing through, he said he would start to vibrate and bump into a classmate and make her vibrate and she would bump into another classmate and make him vibrate. When I asked him if he would travel with the sound he said that he probably wouldn't. In his diagram of the car engine's sound reaching him in a classroom, he sketched circles that represented sound waves and increased in size around the car.

On the final questions Bill sketched a tuning fork and dots (representing air particles) that were close together and labelled them "compressions." Next to the compressions he drew dots that were farther apart and labelled them "rarefactions." He did not indicate the direction of the sound or the particles. To show how a loud, low frequency sound would be represented on an oscilloscope he drew large peaks and troughs which were close together. His sketch corresponded to how a loud, high frequency sound would be represented on an oscilloscope. He said a sonic boom was produced "when you moved faster than the speed of sound and built up a wave that exploded."

On the prior questions Bill had a confused conceptualization of sound waves. He was aware of the term *sound waves* and included them in his diagram of the sound of howling wolves travelling to a tent. Although he said that sound travelled as a wave and could rebound off objects, he provided no details. He did not state that sound travelled as a compressional wave creating a series of compressions and rarefactions, that sound waves could bend around objects, and that sound spread out in all directions from a source.

On the midpoint sound test Bill had a confused conceptualization of sound waves. He stated correctly that sound travelled as a compressional wave and created compressions but he did not mention rarefactions. He knew that sound waves could travel around a corner by echoing off walls or bending. The ripple tank demonstration reinforced his idea that sound travelled as a wave. He cited the demonstration in his argument that sound travelled as a wave. He did not mention the process of sound waves spreading out to explain why a firecracker was much louder if it is set off 1 metre away that 1 kilometre away. Although he said the *slinky demonstration* showed that sound travelled as a compressional wave, he could not explain how. Bill said that the oscilloscope made sound look like a transverse wave rather than a compressional wave, but he did not distinguish between the two wave forms. In attempting to sketch how a quiet, high frequency sound would appear on an oscilloscope, he sketched a low, high frequency sound. He had difficulty distinguishing between how an oscillscope represented loudness and pitch.

On the final questions Bill had a confused conceptualization of sound waves. Although he retained his idea that sound travelled as a wave, his description of sound waves was limited to a sketch of compressions and rarefactions. In his diagram of sound travelling from the motorcycle into the restaurant he did not include waves and did not indicate that sound spread out in all directions. He recalled that sounds could be heard even when the source was out of sight because waves could bend around objects or "ping pong" off walls to travel around corners. He also remembered that a sound became quieter as its energy spread out. In sketching how a loud, low frequency sound would appear on an oscilloscope, he drew a wave that represented a loud, high frequency sound. He had difficulty recalling how an oscilloscope represented a sound's pitch and loudness.

4.2.7 The Combined Journey

4.2.7.1 Reception of Sound -- the ear's anatomy and physiology

On the prior questions Bill's diagram of the ear consisted of sound waves arriving at the (ear flap) and passing to the eardrum which was connected to the brain and he said "the ear detected sound by vibrations in the eardrum." He said humans could not hear all sounds and used a dog whistle as an example of something that produced a sound that dogs could hear, but humans could not.

Following instruction about the characteristics and transmission of sound, but prior to discussion of the ear, Bill's ear design consisted of an outer ear, a large opening leading to an eardrum, and a tube that continued to the brain. His description of the function of the ear was that the eardrum vibrated to detect the loudness and pitch of a sound. He included a noise flap to eliminate unwanted sounds "of parents and teachers."

On the midpoint ear quiz Bill labelled the indicated ear structures correctly. On the fill-in-the-blank section of the quiz he said that: the part of the ear that is filled with fluid is the "cochlea"; the part of the ear that collects the sound is called the "ear flap"; the semi-circular canals help control our sense of "balance"; the thin membrane that vibrates when hit by sounds is the "eardrum"; the name of the nerve that connects the ear to the brain is the "auditory nerve"; and the section of the ear that consists of the hammer, anvil, and stirrup is the "middle ear." Bill said the size of the hairs in the cochlea determined a person's audible range. For the sketch of the cochlea, he drew tiny hairs of different lengths. He incorrectly indicated that the long hairs detected high pitched sounds and the short hairs detected low pitched sounds. Bill described the path of the sound of the whistle as being "scooped" by the ear flap, the sound made the eardrum vibrate and went through the ossicles to the semicircular canal "where it maintains it's [its] balance." He said the sound then entered "the cochlea to determine the pitch and then through the auditory nerve to the brain." He added that the reception of sound was "all done in a matter of seconds." He said the main advantage of the eardrum being bigger than the cochlea's oval window was that it allowed the ear "to pick up [detect] more sound."

On the final questions Bill drew an ear flap, wax glands, ear canal (unlabelled), eardrum, ossicles, cochlea, auditory nerve, and brain in the proper sequence. He explained that the eardrum detected pitch, the ossicles maintained balance, and the cochlea detected pitch and frequency. He said the cochlea had tiny hairs that detected a sound's pitch and frequency and that the cochlea's short hairs detected high-pitched sounds.

On the prior questions Bill had a confused conceptualization of both the ear's anatomy and physiology. The structures he included in his ear diagram were an ear flap, eardrum, and the brain. He had to guess what structures composed the ear. On the prior questions Bill had a confused conceptualization of sound. He thought that sound vibrated, travelled in waves, and echoed off objects as it travelled. He did not discuss pitch, frequency, or loudness in his description of sound transmission. Similarly, his description of the ear's physiology was confused with no mention of how the loudness and pitch of a sound would be detected. His explanation of what happened to the sound from the time it arrived at the ear flap until it reached the brain was limited to stating that sound was detected by vibrations in the eardrum.

Following instruction about the characteristics and transmission of sound, but prior to discussion of the ear, Bill had a confused conceptualization of both the ear's anatomy and physiology. Bill had not seen a picture or model of the human ear so he was forced to guess what structures comprised an ear. In addition to the ear flap, eardrum, and the brain that he included on the prior questions, his ear diagram contained tubes and a flap (to filter out unwanted sound). In his sketch and description of how an ear worked, Bill attempted to incorporate two properties of sound, pitch and loudness. He did not say the eardrum's function was to detect vibrations. Instead, he said that the eardrum detected the pitch and loudness of a sound, but he did not say how. With confused knowledge of sound transmission and human anatomy, Bill tried to create an ear.

On the midpoint ear quiz Bill had a *scientific* conceptualization of the ear's anatomy. He correctly labelled the indicated parts on a diagram of the ear. His conceptualization of the ear's physiology was confused. While many of his ideas of the functions of the parts of the ear matched the *scientific* perspective, there were several mismatches. On the fill-in-the-blank section of the quiz he correctly listed the ear structure associated with each function. He correctly sketched how the hairs in an uncoiled cochlea would appear but reversed the respective pitches the hairs would detect. He said incorrectly that the short hairs would detect low pitched sounds, and the long hairs would detect high pitched sounds. In describing the path of sound through the ear, he stated that the sound would pass through the ossicles to the semicircular canals to maintain balance before reaching the cochlea. He had mistakenly linked the sense of balance directly to the sense of hearing.

On the final questions Bill had a *scientific* conceptualization of the ear's anatomy. His diagram of the ear was drawn clearly, labelled completely and correctly with no omissions of parts discussed in class and even included the semicircular canals. Bill had a confused conceptualization of the ear's physiology. His description of what happened to the sound as it passed through the ear to the brain was less detailed than on the midpoint ear quiz. He said correctly that the eardrum vibrated in response to a sound and that the cochlea had tiny hairs that detected the pitch of a sound. He said correctly that the short hairs of the cochlea detected high pitched sounds, but he stated incorrectly that the ossicles helped maintain balance. He did not describe the function of the ear flap or auditory nerve.

4.2.8 Summary of Bill's Journeys

Over the time of this investigation, Bill's conceptualizations of sound related topics evolved in several patterns. He had a scientific conceptualization of the relative speeds of sound and light throughout the study. For the topics of sound transmission, sound passing through the states of matter, echoes, frequency ranges and the anatomy of the ear, he changed from a confused conceptualization on the prior questions to a scientific conceptualization on the midpoint sound test (or midpoint ear quiz) and the final questions. He changed from a confused conceptualization of causes of hearing loss on the prior questions, to a *scientific* conceptualization on the midpoint sound test and finally a confused conceptualization on the final questions. For the topics of sound waves, frequency and pitch, and the ear's physiology, Bill started with confused conceptualizations on the prior questions and continued to have confused conceptualizations on the midpoint sound test (or midpoint ear quiz) and final questions.

4.2.9 Discussion of Bill's Journeys

Overall, Bill's conceptualizations of sound and hearing were closest to the *scientific* perspective on the midpoint sound test and midpoint ear quiz. Bill exhibited a shift in his conceptualization of the ear's anatomy. Initially, he knew only that the ear consisted of an ear flap and eardrum which somehow transferred information about sound to the brain. On the test and final questions he knew all the parts of the ear and their sequence from the ear flap to the brain.

Bill's conceptualization of echoes represented in his answers to the prior questions formed the basis for how he thought sound travelled. He recognized that echoes were rebounded sounds. He developed a *scientific* conceptualization of how echoes occurred and why their loudness diminished. However, his answers to the prior questions led him to a confused conceptualization of frequency and pitch. On the prior questions he thought that pitch and loudness meant the same thing. Although he remembered definitions of terms associated with frequency and pitch, his confusion between pitch and loudness continued to the final questions. When asked how the pitch could be changed he discussed factors affecting loudness instead. In spite of Bill's eagerness to learn and the teacher's emphasis that pitch and loudness described different properties of sound, he did not distinguish between pitch and loudness.

Characteristics of Sound

	Prior Questions		Mid-point Sound Test		Final Questions
Frequency and Pitch	Δ	-->	Δ	-->	Δ
Frequency Ranges	Δ	-->	Δ	-->	□

Transmission of Sound

	Prior Questions		Mid-point Sound Test		Final Questions
Particle Collisions	Δ	-->	Δ	-->	Δ
States of Matter	Δ	-->	Δ	-->	Δ
Waves	-	-->	Δ	-->	Δ
Echoes	Δ	-->	Δ	-->	Δ
Sound vs. Light	Δ	-->	Δ	-->	Δ

Reception of Sound

	Prior Questions		Ear Diagram		Mid-point Ear Quiz		Final Questions
The Ear's Anatomy	Δ	-->	Δ	-->	O	-->	O
The Ear's Physiology	Δ	-->	Δ	-->	Δ	-->	Δ
Hearing Loss / Deafness	Δ	---------------->			Δ	-->	Δ

Δ = confused conceptualization

□ = incomplete conceptualization

O = *scientific* conceptualization

- = no conceptualization (student provided no information about a particular concept)

Table 4.2: Mary's Sonic Journeys

4.3 Mary's Journeys: Orienteering Without a Compass

4.3.1 Mary's Background

Mary earned a "C+" in the first term and a "C-" in the second term. In the first term her test scores averaged 63% and her overall term mark was 67%. Her second term score was 55% with an average of 53% on tests. Mary's effort and results were inconsistent. She said that she had difficulty in math and English. She expressed herself better orally than in writing. She enjoyed learning. She focused on finding the *right answer* and wanted her successes acknowledged. Mary played the flute in the high school band and she had played the guitar when she was in elementary school. I selected her because I thought she would complete all the activities making up this study.

4.3.2 Introduction to Mary's Journeys

For all the sound topics Mary's prior ideas did not match the *scientific* conceptualizations. On the midpoint and final questions she had confused conceptualizations of all the sound topics except for the *frequency ranges* and the *ear's anatomy*. Her journeys resembled *orienteering without a compass*, meaning that she was given the information (like a map), but she created her own route which tended not to approach the *scientific* conceptualization. Although she was provided with information and instructions in class (like a map and compass), Mary's ideas about sound often seemed unaffected by classroom instruction. In other instances the classroom instruction and teacher demonstrations appeared to add to the confusion in her conceptualizations of sound and hearing.

4.3.3 Orienteering Without a Compass

4.3.3.1 Characteristics of Sound -- frequency and pitch

On the prior questions Mary thought that all sources of sound vibrated and made noise. When asked to compare the sound made by a mosquito to the sound made by a crowd at a hockey game, she said "the mosquito has a high pitched buzzing sound." She did not describe the crowd's sound at a hockey game or say what the pitch of a sound described. In order to produce a higher pitched sound she stated "you should adjust the volume to set it how high you want it to go." When asked how the pitch of an ambulance's siren would change as the ambulance approached and passed her, Mary said the sound became louder "because it [the ambulance] is getting closer."

On the multiple choice section of the midpoint sound test Mary knew that all sources of sound "vibrate" and that frequency is measured in "hertz." She said incorrectly that the frequency of an object is "how high it swings" and a pipe organ has long pipes to produce "higher notes." Her description of the relationship between pitch and frequency was that high freqency meant high pitch and low frequency meant low pitch. She suggested that "using a shorter string and tightening it [guitar string]" would produce a higher pitched sound on a guitar. To change the pitch of a drum she said "you hit it [the drum] on a certain spot and it will change the volume and it depends on how hard you hit the drum with your drum sticks." She defined vibration as "something that moves back and forth rapidly." In the frequency lab various factors were investigated to see how they affected the frequency of a pendulum. Mary said the purpose of the frequency lab was "you can't hear it [sound of a pendulum] at human level . . . unless you put it [pendulum] right to your ear." On clarification she said that people could not hear the pendulum's sound because it was too quiet. She had no answer for how the length of a pendulum affected its frequency.

On the final questions Mary said that high pitch referred to high frequency and low pitch referred to low frequency. She explained that to play a higher pitched note on a flute "you make a smaller hole and blow harder and use your stomach muscles." She said the purpose of the frequency lab was "to detect the sound with our ears." On clarification she said that the frequency lab explained how the hairs in the cochlea worked, that the short hairs detected high pitched sounds and the long hairs detected low pitched sounds. She said a pendulum's frequency was affected by its length, that a short pendulum had a higher frequency than a long pendulum. For the situation in which the pitch increased as a drain pipe filled with water, Mary said that "when it [water falling from a tap] starts hitting the water it [the pitch] gets even higher" but she could not explain why.

On the prior questions Mary's ideas about frequency and pitch did not fit the *scientific* perspective and were confused. Although she knew that sources of sound vibrated and that pitch described a sound, she linked pitch to loudness not frequency. Evidence that she used the terms pitch and loudness interchangeably was that she thought that a higher pitched sound on a guitar could be produced by increasing the volume. Also, she said that the pitch of an approaching ambulance's siren would become louder. She did not realize that pitch referred to frequency and that the pitch of a siren would increase as the ambulance approached and decrease as the ambulance moved away. Mary did not know that pitch described the frequency of a sound. Thus it was not surprising that she did not know how the frequency of an object could be changed.

On the midpoint sound test Mary had a confused conceptualization of frequency and pitch. Although she knew that sources of sound vibrated and that frequency was measured in hertz, she could not define the term frequency. Mary recognized that pitch corresponded to the frequency of a sound, but some of her ideas for changing the pitch of a musical instrument indicated that she still associated pitch with loudness. She suggested that hitting a drum harder would increase its pitch, not realizing that the loudness would increase. She did not know how a pendulum's length affected its frequency and she was unable to explain how the length of an air column affected the pitch of a wind instrument and how a drum's size affected its pitch. Mary's experience playing the guitar enabled her to provide two correct methods for increasing the pitch of a guitar (using a shorter string and tightening the string).

On the final questions Mary had a confused conceptualization of frequency and pitch. She knew that the frequency of a sound determined the pitch. Her experience playing the flute helped her explain how to change the pitch of a flute correctly. Having learned about the role of the tiny hairs in the cochlea in detecting pitch, on the final questions Mary was aware of the purpose of the frequency lab, that the length of a pendulum (or hair) determined the frequency at which it vibrated. Her explanation for why the pitch increased as a drain pipe filled with water provided evidence that her conceptualization was confused. She thought that as the water level in the drain pipe increased it made sense that the pitch also increased. She did not link the drain pipe situation to the frequency lab, that the pitch increased because the height of the air column above the water decreased (corresponding to a short pendulum vibrating at a higher frequency).

4.3.3.2 Transmission of Sound -- via particle collisions and through the states of matter

On the prior questions from a list of possibilities for how sound travelled (like a baseball being thrown from one place to another; like the form of heat transfer called conduction; like the form of heat transfer called convection; like sunlight passing from the sun to earth; or something else) Mary selected *like a baseball being thrown from one place to another*. She drew trees between the howling wolves and her tent and said the sound travelled to the tent because "the vibrations that could go through solids, gases and liquids." Mary thought that "sound could vibrate through empty space" and any state of matter. On clarification, she said that empty space gave the sound "more room to vibrate through." She knew that sound could pass through a solid wall because she could hear noises from another classroom during science class. She said that "the sound could vibrate through the walls as it goes." Her response to the question of whether she could hear sounds underwater was "when I'm underwater I can hear people yelling and talking, but not clearly."

On the midpoint sound test Mary said that sound transmission was similar to heat conduction because "they both have to do something about the air." For the scene in which a spaceship was struck by a missile followed shortly by the sound of an explosion, Mary said the problem was that the sound was infrasonic, too low for people to hear. She said she knew sound could pass through water because she could hear underwater and because "you can hear through solids, liquids, and gases, but not a vacuum." She said that sound did not travel in the form of *sound particles* because she could not hear sounds during the vacuum pump demonstration. She thought that sound travelled like transverse waves. Mary said that the ripple tank demonstration showed that sound travels in the form of waves "because the water rebounds from whatever it hits and makes odd shaped circles." When asked to consider her classmates and herself to be air particles as a sound passed, she said "we would pass through each other unaffected." On clarification, she said that the ripple tank demonstration had shown that waves weren't changed when they passed through each other.

On the midpoint sound test Mary faced a problem. It was suggested that sound should pass through gases the fastest and solids the slowest which is the reverse of what is observed in nature. She said the description was correct, but she provided no reasons. Mary was asked to sketch, label, and describe how the sound of a loud car could reach her in a classroom first when the room's window was open, and then when the window was closed. For the situation of an open window she drew circles spreading out from the car, another set of circles spreading out midway between the car and window, overlapping with the first set of circles, and in the gap created by the open window she sketched a small set of circles spreading out. Her description of sound transmission was "it's [sound transmission] a rarefaction because the particles are spreading and pass through a solid unaffected because the window is open." For the situation of a closed window, she drew overlapping circles of equal size between the car and classroom. She said the sound would not be affected as it passed through the solid wall. She did not explain how the closed window decreased the sound's loudness.

On the final questions Mary did not compare heat conduction and sound transmission. During probing she said she could not remember how heat conduction occurred. She said that on the moon you would not hear the sound of an asteroid striking the other side because "your ears would probably be plugged due to the height." (She was referring to how changes in altitude resulted in pressure changes which affected hearing.) When asked whether two rocks banged together underwater would produce an audible sound, she said "yes, I can hear it [the sound of the rocks banging underwater] because sound can travel through liquids, but not as fast." She said that *sound particles* existed "because they can be in our ear muscles and ear parts." On clarification, she said that she meant there were openings in our ears that allowed *sound particles* to pass through.

On the final questions Mary faced a problem about sound transmission accompanied by three diagrams showing how sound would travel through a solid, a liquid and a gas. It was suggested that sound should travel fastest through gases because there were big enough gaps between the particles to allow sound to pass through easily. It was also suggested that sound could not pass through a solid because the particles were *locked together* without any gaps to allow the sound to pass through. She agreed that it would be easier for the "*sound particles* to pass between the gaps." Mary said that sound passes fastest through gases "because there are bigger gaps between the particles of a gas so this theory matches the description." When asked to sketch how the sound of a loud motorcycle reached a person in a restaurant, Mary drew similar sized, overlapping circles from the motorcycle through the open door to the person in the restaurant. She said the sound went through the gaps. She thought that *sound particles* travelled with the sound to the person in the diner.

Mary's prior ideas of sound transmission were confused. Although she knew that sources of sound vibrated and described sound "expanding" in all directions, she did not know that sound transmission required particles and that a compressional wave caused particles to collide with neighbouring particles. She thought that sound travelled like a physical object rather than energy in the form of waves. Mary thought that sound could "vibrate" through anything. She said correctly that sound could pass through solids, liquids and gases, but incorrectly thought sound could pass through a vacuum. Mary did not know that sound could change speed. Not only was she unaware that sound transmission required particles, she did not know that the different spacings of particles in solids, liquids and gases affected the speed of sound through each state.

On the midpoint sound test Mary had a confused conceptualization of sound transmission. Although she stated correctly that sources of sound vibrated, sound transmission required particles and was similar to heat conduction, she did not describe what happened to particles as sound passed. She did not indicate that a compressional wave created compressions and rarefactions and caused particles to collide with each other. Although at one point she correctly said that *sound particles* did not exist, later she said that particles (of air) could carry the sound through a solid wall. She correctly stated that sound spread out, but her description was confused. She reasoned that sound "expanded" (spread out) because the particles that sound travelled through spread out creating rarefactions. Mary had a confused conceptualization of how sound passed through the states of matter. She knew that sound required particles and could pass through all states of matter, but not through a vacuum. She said that the vacuum pump demonstration had "proved" that sound could not pass through a vacuum. Although she knew that sound passed fastest through solids, slowest through gases, and not through a vacuum, she did not realize that sound transmission required particle collisions and that the different spacings of the particles in each state of matter determined the speed of sound. Her confused ideas of sound transmission through the states of matter corresponded to her confusion about the role of particles in sound transmission.

On the final questions Mary's conceptualization of sound transmission was confused and similar to her ideas on the midpoint sound test. She stated correctly that sources of sound vibrated, sound "expanded" (spread out) and required particles, and sound transmission was similar to heat conduction. She could not explain what effect a sound had on the particles as it passed, and she did not mention that sound travelled as a compressional wave. She accepted the idea that sound travelled in the form of *sound particles*, special particles that carried sound. She thought that *sound particles* travelled with a sound wave to the listener and were involved in human hearing, passing from the ear flap to the brain. In her diagram of sound travelling from a motorcycle into a restaurant she represented sound waves as overlapping similar sized circles which did not match the diagrams in her notebook of waves spreading out. Mary had a confused conceptualization of sound transmission through each state of matter. She recalled that sound could change speed, pass through all states of matter, and not pass through a vacuum. She could not explain the behaviour of sound in terms of waves and particle collisions. She mistakenly thought that sound passed fastest through gases and slowest through solids. Her mistake corresponded to the incorporation of *sound particles* into her conceptualization of sound transmission. She agreed with the idea that it was easier for *sound particles* to pass through gases because gases contained larger gaps than solids.

4.3.3.3 Transmission of Sound -- waves

At no time on the prior questions did Mary mention that sound travelled in the form of sound waves. She did not include sound waves in her diagram of how the sound of the wolves' howling reached the tent.

On the midpoint sound test Mary said that the ripple tank demonstration gave evidence that sound travelled in the form of waves. She said the demonstration showed how sounds could spread out, pass through each other and "rebound off whatever they hit." She did not mention that the ripple tank demonstration showed how waves bent around objects. Mary said that sound travelled as a transverse wave because the oscilloscope demonstration showed "that sound waves looked like curvy lines." For how a quiet, high frequency sound wave would appear on an oscilloscope, Mary drew large peaks and troughs spread out from each other. She identified the lowest pitched sound, quietest sound and noise based on their oscilloscope representations. She said a firecracker sounded louder one metre away than one kilometre away because "it [sound] didn't have to go as far." In her diagram of a car's sound entering a classroom she drew circles that overlapped with each other and headed towards the classroom. She said "the sound travels as rarefactions because the particles are spreading out and passing through the solid wall."

To explain how sound could reach her even when she could not see the sound source, on the final questions Mary said the sound "vibrates and expands." Her sketch of how a loud, low frequency sound would appear on an oscilloscope featured a large peak and trough. She did not attempt to sketch a vibrating tuning fork or explain how the tuning fork affected the surrounding particles. Her diagram of a motorcycle's sound entering a restaurant consisted of overlapping, similar sized circles between the motorcycle and the customer in the restaurant. On clarification, she explained that the circles represented sound waves as she remembered them from the ripple tank demonstration. At no time on the final questions did Mary mention the terms compressional wave, compressions or rarefactions.

On the prior questions Mary had no conceptualization of sound waves. She was unaware of the term sound waves and did not use sound waves in her description of sound transmission or the properties of sound.

On the midpoint sound test Mary had a confused conceptualization of sound waves. In her description of sound transmission she said that sound expanded, but she did not mention sound waves, or explain how sound waves were created, how they affected particles, and how they accounted for sound bending around a corner and becoming quieter. The oscilloscope demonstration convinced her that sound travelled as a transverse wave. She was not aware that sound travelled in the form of a compressional wave and she did not know how a compressional wave created regions of compressions and rarefactions. She knew that particles were spread out in rarefactions. She combined her ideas about rarefactions with her idea that sound spread out and concluded that sound travelled in the form of rarefactions. To explain why a sound became quieter as it travelled Mary did not mention that the sound's energy spread out. She recalled correctly that waves could pass through each other unaffected, but she did not remember that waves could bend around objects. Although Mary was able to identify the three different sounds indicated on the test based on their oscilloscope representations, her representation of a quiet, high frequency sound corresponded to a loud, low frequency sound.

On the final questions Mary had a confused conceptualization of sound waves. Her idea that sound "expanded" corresponded to sound waves spreading out from a source, but she did not mention that sounds: travelled as compressional waves; created compressions and rarefactions; could bend around corners; could pass through each other; or became quieter the farther they travelled. Her diagram of sound waves passing from the motorcycle into the restaurant consisted of overlapping circles that remained the same size between the motorcycle and restaurant. Her sketch did not match the wave representations of sound waves in her notebook which was based on the ripple tank demonstration with ever increasing circles spreading from the sound source.

4.3.3.4 Transmission of Sound -- echoes

On the prior questions Mary described an echo as "a sound that bounces off of whatever it hits and keeps on going." She said she could hear a car with loud music blaring from its stereo even after it had driven out of sight around a corner. She thought that sound could travel around a corner by "expanding."

On the midpoint sound test Mary said that several ways that sound could go around a corner were "sound can rebound off walls and they can go through each other unaffected or go through solids." Mary explained that an echo occurred "when a sound just rebounds off the walls and gets quieter each time it hits." When asked whether an echo was louder or quieter than the original sound, she said that the echo was louder because "each time it [the original sound] hits it's a loud sound and they add together." She based her answer on her experiences listening to echoes in a local tunnel. She said echolocation described the pitch of an echo.

On the final questions Mary said that "sound can vibrate and expand to get around corners." She said that echoes were produced by a sound vibrating off the surroundings and were louder than the original sound. She described sonar as "detecting the sound of an object." On clarification, she said sonar was used to figure out where a sound was coming from.

On the prior questions Mary had a confused conceptualization of echoes. She correctly described an echo as a rebounded sound but provided no reasons for why an echo was quieter than the original sound. She did not include echoes in her explanation for how sound could travel around a corner.

On the midpoint sound test Mary had a confused conceptualization of echoes. She described echoes as rebounded sounds and included echoes in her explanation of how sound could travel around a corner. At one point she said that echoes were quieter than the original sound, but later she cited her experiences in a tunnel as proving that echoes were louder than the original sound. Mary's knowledge of echolocation was limited to stating that it involved echoes. She could not explain what echolocation was used for or how it worked. She did not include sonar as an example of echolocation.

On the final questions Mary had a confused conceptualization of echoes which was limited to knowing that echoes were sounds that had bounced off something. As on the sound test, she was certain that echoes were louder than the original sounds. She did not use echoes to explain how sound could travel around a corner. Although she knew sonar involved sound, she did not describe how it worked, that it involved ultrasonic sounds and echoes and was used to determine the location of objects.

4.3.4 Orienteering With a Compass

4.3.4.1 Characteristics of Sound -- frequency ranges

On the prior questions Mary thought that ultrasonic sounds were louder sounds. She thought that she could hear all sounds.

On the midpoint sound test Mary answered correctly: that infrasonic sounds were "too low to be heard by humans"; that a "bat" uses echolcation to fly and hunt in the dark; and that an earthquake is an example of an "infrasonic sound." As examples of uses of ultrasonic sounds she listed a dog whistle, elephants communicating, and a piccolo. During probing she said that while watching a nature show on television she had learned that elephants used ultrasonic sounds to communicate. She stated that the frequency she could hear was 37 Hz. Mary said that echolocation was "how high the pitch and frequency of an echo was."

On the final questions Mary said that ultrasonic meant "it's above human sound." On clarification she said that humans could not hear ultrasonic sound. She listed a dog whistle, tuba, and elephants communicating as three uses of ultrasonic sounds. She said her audible range was 27 Hz to 17 000 Hz. She said that sonar is used to detect the sound of an object. On clarification, she said that sonar could determine where a sound was coming from, but she did not know how sonar worked.

On the prior questions Mary had a confused conceptualization of the frequency ranges. She thought that she could hear all sounds. She was not aware of the infrasonic and audible sound ranges. Consistent with her confusion between loudness and pitch, Mary thought that ultrasonic sounds were louder sounds.

On the midpoint sound test Mary had a confused conceptualization of the frequency ranges. She could not define each frequency range in hertz. She could not identify the sound frequencies she could hear and thought her audible range consisted of only one frequency, 37 hertz. She knew that infrasonic sounds were too low pitched to be heard and she provided two correct examples of ultrasonic sound. Her third example of an ultrasonic sound, a piccolo, was incorrect. A piccolo produces high pitched, but audible sounds. She did not use sonar as an application of ultrasonic sound or include sonar in her description of echolocation.

Mary's conceptualization of the frequency ranges most closely matched the *scientific* perspective on the final questions. She correctly defined the audible range in terms of the frequencies that she could hear. She provided several correct examples of ultrasonic sounds and knew that they were too high pitched to be heard by humans. During probing she said that infrasonic sounds were too low to be heard and she correctly listed earthquakes as an example of infrasonic sound. The only noted weakness in her conceptualization of the frequency ranges was that she did not indicate that sonar was an application of ultrasonic sound.

4.3.5 Orienteering With and Without a Compass

4.3.5.1 Reception of Sound -- the ear's anatomy and physiology

On the prior questions Mary drew a diagram of the ear which consisted of an ear flap (unlabelled) and a tube that led to the brain. Her description of human hearing was "because of your brain functioning your brain defines something, it just works." She said that humans could hear almost everything and added, "right now I can hear a buzzing noise like a screeching sound."

Following instruction about the transmission and characteristics of sound, but before discussion of the ear's anatomy and physiology, Mary's ear design consisted of an ear flap (unlabelled) which led to a tube into an area that detected a sound's pitch and finally to nerves that led to the brain. Mary described human hearing as "the sound hits the sound system, passes through nerves to the brain which catches the sound." During probing, she said that she did not know how "the brain catches the sound."

Mary labelled all the indicated parts correctly on the diagram of the ear provided on the midpoint ear quiz. She answered most of the fill in the blank questions incorrectly. Her correct answers were the "auditory nerve" connects the ear to the brain, and the hammer, anvil, and stirrup are located in the "middle ear." Her incorrect responses were: the part of the ear that is filled with fluid is the "oval window"; the part of the ear that collects the sound is called the "cochlea"; the semi-circular canals help control our sense of "hearing"; and the thin membrane that vibrates when hit by sounds is the" anvil." In relation to human hearing, Mary said the sound of the whistle "stayed the same all the way through the ear." On clarification, she said she meant that the ear did not change the sound, that the sound was the same outside the ear as "what the brain hears." She provided no answer for the major advantage of the eardrum being much larger than the oval window. She said "our audible range is lower than other animals and animals can detect sound better than we can because we are different." On clarification, she said that she did not know how humans and other animals differed. Her sketch of an uncoiled cochlea included tiny hairs of different lengths. She said the long hairs detected high pitched sounds, and the short hairs detected low pitched sounds.

On the final questions Mary drew an ear flap, ear canal, eardrum, hammer, anvil and stirrup, cochlea and cochlear nerves leading from the cochlea to the brain. (In class we used the term auditory nerve, not cochlear nerves, but she said the book she used for her hearing device project had labelled them cochlear nerves.) She also included semicircular canals and the eustachian tube. In describing how the ear functioned she said "when it [sound] hits your ear, the brain goes 'you have a sound' and when it hits your ears it's already in your ears." On clarification she said the sound went quickly to the brain. She said the ear works "by the fluid and the sound." During probing she said "there's fluid in the cochlea and the sound gets in there and makes the fluid do something." She said she had no idea what happened to the cochlea's fluid, but she correctly answered that the short hairs in the cochlea detected high pitched sounds.

On the prior questions Mary had a confused conceptualization of the ear's anatomy. She said that she had never seen the inside of an ear before. Related to her limited knowledge of sound transmission and the properties of sound, her conceptualization of the ear included only an ear flap and a brain and lacked detail. Mary had little knowledge of the ear's physiology. Mary knew that the brain interpreted information about a sound from the ear flap. Related to her lack of knowledge of the ear's anatomy and the properties of sound (e.g. pitch and loudness), Mary was unable to explain what happened to the sound after it arrived at the ear flap until it reached the brain.

Following instruction about the transmission and characteristics of sound, but prior to discussion of the ear, Mary had a confused conceptualization of the ear's anatomy. Her diagram resembled her sketch on the prior questions. She included an ear flap and a brain. The major addition to her diagram was a series of nerves leading from the ear flap to the brain, but she did not include an ear canal, eardrum, ossicles or cochlea. Mary had a confused conceptualization of the ear's physiology. She thought that the sound echoed through the ear flap until it reached an area that detected the pitch of a sound. She thought the brain then "caught" and interpreted the sound. One change from her earlier ideas of the ear's function was that she included pitch as a property of sound that the ear detected. Related to her lack of knowledge of the ear's anatomy, Mary was unable to explain how the ear detected the pitch of a sound and she did not discuss how sounds of different loudness were detected.

On the midpoint ear quiz Mary had a *scientific* conceptualization of the ear's anatomy. She correctly labelled an ear flap, an ear canal, an eardrum, the ossicles (hammer, anvil and stirrup), the cochlea, oval window, and the auditory nerve on the diagram provided on the midpoint ear quiz. Also, she sketched correctly how an uncoiled cochlea would appear. Mary had a confused conceptualization of the ear's physiology. As mentioned, she correctly sketched how an uncoiled cochlea would appear, but she said incorrectly that the short hairs detected low pitched sounds and the long hairs detected high pitched sounds. She did not transfer what she knew about the cochlea's role in detecting pitch to explain why human's audible range differed from other animals. When asked to describe what happened to a sound as it passed through the ear, she did not discuss the cochlea's role in detecting the pitch of a sound. Instead she said that the sound went straight to the brain. Surprisingly, she did not discuss the role of the ear flap, ear canal, eardrum, ossicles, cochlea, or auditory nerve even though she had correctly identified these structures on the diagram of the ear. She was not able to link the ear's physiology and anatomy.

On the final questions Mary had a *scientific* conceptualization of the ear's anatomy. Her diagram was complete and the structures were drawn in the proper sequence. Not only did she include the structures of the ear related to hearing, she added the semicircular canals above the cochlea and the eustachian tube leading from the middle ear to the throat. Even two weeks after completing the unit on sound and hearing, Mary produced an accurate and precise representation of the ear's anatomy. Mary had a confused conceptualization of the ear's physiology. Her conceptualization was similar to her ideas earlier in the study. She said the sound hit her ear and her brain said, "you have a sound." Although she said correctly that the short hairs of the cochlea detected high pitched sounds, she was unable to describe the cochlea's role in hearing.

On the final questions, although Mary had a *scientific* conceptualization of the ear's anatomy, she was unable to link the structures of the ear to their corresponding roles in detecting sound and passing the information to the brain.

4.3.6 Discussion of Mary's Journeys

For all of the sound topics Mary began with confused conceptualizations. Her journeys resembled *orienteering without a compass* and she tended not to approximate the *scientific* conceptualizations. She was provided with information and instructions in class (like a map and compass), yet her ideas about sound often seemed unaffected by classroom instruction. Instead, her prior ideas and experiences dominated her conceptualizations of sound. In cases where her prior ideas matched the *scientific* perspective (such as describing echoes as rebounded sounds and recognizing that sources of sound vibrate) she retained these *correct* ideas throughout the study. For example, at all stages of the study she used her idea that sound "expanded" to explain various properties of sound. When her prior ideas conflicted with the *scientific* perspective she had difficulty developing *scientific* conceptualizations. As an example, her experiences in a tunnel convinced her that an echo was louder than the original sound. Her musical background, playing the flute and guitar, enabled her to know how to change the pitch of those instruments, but she could not extend her knowledge to explain how the pitch changed in other situations. In sum, Mary's *sonic journey* was shaped and limited by her prior ideas and experiences.

Characteristics of Sound

	Prior Questions		Mid-point Sound Test		Final Questions
Frequency and Pitch	Δ	-->	O	-->	O
Frequency Ranges	□	-->	O	-->	O

Transmission of Sound

	Prior Questions		Mid-point Sound Test		Final Questions
Particle Collisions	□	-->	O	-->	O
States of Matter	O	-->	O	-->	O
Waves	-	-->	O	-->	□
Echoes	Δ	-->	O	-->	O
Sound vs. Light	□	-->	O	-->	O

Reception of Sound -- The Ear: Structure and Function

	Prior Questions		Ear Diagram		Mid-point Ear Quiz		Final Questions
The Ear's Anatomy	Δ	-->	Δ	-->	O	-->	O
The Ear's Physiology	Δ	-->	Δ	-->	O	-->	O
Hearing Loss / Deafness	Δ	----------------		-->	O	-->	Δ

Δ = confused conceptualization

□ = incomplete conceptualization

O = *scientific* conceptualization

- = no conceptualization (student provided no information about a particular concept)

Table 4.3: Frank's Sonic Journeys

4.4 Frank's Journeys: Drag Racing

4.4.1 Frank's Background

Frank earned "A's" in both the first and second terms. In science his overall marks and scores on tests, labs, and homework for each term were all over 90%. He organized his work well and completed it on time. Frank played the drums in the school band. He learned new science concepts quickly and expressed himself clearly, orally and in writing. Frank was a confident, but modest student, willing to help his classmates learn. He was selected because he would complete all the activities making up this study. He said he found the course "fairly easy" but enjoyed learning "new things."

4.4.2 Introduction to Frank's Journeys

Frank came to class equipped with a wealth of information about sound (and many science-related topics). With his zest for learning, Frank was able to develop links rapidly between new information presented in class and his prior knowledge of sound. For most of the sound topics, Frank's prior ideas approximated a *scientific* perspective. By the midpoint questions he presented a *scientific* conceptualization for each sound topic. One might say that the developments in Frank's conceptualizations fit the journey of a drag race. He moved quickly and did not have to travel far to reach the *scientific* perspective for most topics related to sound and hearing. The only exception to the journey of a drag race was the change in his conceptualizations of causes of hearing loss.

4.4.3 Frank's Drag Races

4.4.3.1 Characteristics of Sound -- frequency and pitch

On the prior questions Frank said that all sources of sound vibrated to make noise. When asked to compare the sound made by a mosquito to the sound made by a crowd at a hockey game he described the sound in a stadium as "a lot of noise so it has to share it with everyone's ears," and a mosquito's buzzing as "closer to your sense of hearing." On clarification, he said the crowd and mosquito would seem to have the same loudness because the crowd was louder but farther from a person's ears than a mosquito. Frank said the pitch told us "what kind of particles it [the sound] makes vibrate." He said that to produce a higher pitched sound with a guitar he would use a smaller width string or shorten the strings by pinching down with his fingers. For the change in pitch as an ambulance approached with siren blaring he said "when the ambulance goes past the particles have stopped moving and the particles stop moving so they produce no noise." On clarification he said that when the ambulance was too far away no sound would be heard.

On the midpoint sound test Frank correctly recognized that: all sources of sound "vibrated"; frequency was measured in "hertz"; and if the frequency increased the pitch "increased." He defined vibration as "to move back and forth repeatedly." He explained that a sound's pitch depended on its frequency and that as the frequency increased so did the pitch. To produce a higher pitched sound with a guitar he said "you could tighten or shorten the strings." To change the pitch of a drum Frank suggested that some drum heads could be tighter than others. He said that a pendulum was used in the frequency lab because, unlike sources of sound that people can hear, a pendulum vibrates slowly enough that the frequency can be measured. He said he learned that "the longer the rope [pendulum], the longer it took to vibrate and the shorter the rope, the shorter it took to vibrate." On clarification, he said that if a pendulum vibrated quickly it had a high frequency and if it vibrated slowly it had a low frequency.

On the final questions Frank said that a high frequency corresponded to a high pitch and a low frequency to a low pitch. He explained that to increase the pitch of a note on the flute "you can make the flute shorter by opening a hole closest to your mouth or by blowing higher notes." He thought the purpose of the frequency lab was "to observe vibrations and to see what things affected the frequency." For the situation in which a drain pipe was filled with water, he said that the pitch increased as the drain pipe became shorter. On clarification, he said that as the pipe filled with water, "the air [column] above the water became shorter and vibrated faster to produce a higher pitched sound."

On the prior questions Frank had a confused conceptualization of frequency and pitch. Frank used the term vibration in his description of sound, but did not include the term frequency. Although he knew how to produce a higher pitched sound on a guitar and that ultrasonic sounds were high pitched, he did not relate the frequency of a sound to its pitch. Instead, his response that the pitch of a passing ambulance's siren would become quieter indicated that he associated pitch with the loudness of a sound.

On the midpoint sound test Frank had a *scientific* conceptualization of frequency and pitch. He correctly defined the term frequency and described how the frequency of a sound determined its pitch. He did not confuse pitch and loudness. Frank knew how the length affected the frequency of a pendulum. He also provided two correct methods for increasing the pitch of a guitar and one correct way to increase the pitch of a drum.

On the final questions Frank had a *scientific* conceptualization of frequency and pitch. He knew that the frequency determined the pitch of a sound. He correctly explained how to increase the pitch of a flute. He recalled how the length of a pendulum affected its frequency and used this information to explain why the pitch increased as a drain pipe filled with water. Frank knew that as the pipe filled with water, the air column above the water became shorter and that a shorter air column corresponded to a shorter pendulum. He knew that a shorter pendulum and shorter air column would both vibrate at a higher frequency.

4.4.3.2 Characteristics of Sound -- frequency ranges

On the prior questions Frank said that ultrasonic sounds were "so high pitched nobody can hear them and they were used for dog whistles and to determine where substances were underground." He said that humans could not hear sounds that were too high pitched or too low pitched and he did not list the frequencies (in hertz) for any of the frequency ranges.

On the midpoint sound test Frank said that infrasonic sounds were too low to be heard by humans and that earthquakes were an example of infrasonic sound. As examples of uses of ultrasonic sounds Frank said they could be used to "look at a pregnant lady's fetus, for crushing kidney stones, and for sonar." He said the frequencies he could hear were from 20 Hz to 20 000 Hz and said that echolocation was another use of ultrasonic sound.

On the final questions Frank said that ultrasonic sound meant "sounds too high for us to hear." He said that ultrasonic sounds could be used "to crush kidney stones, for dog whistles, and to look at babies in pregnant women." He listed his audible range as 20 Hz to 20 000 Hz. He said that sonar was used for echolocation and that "armies use sonar to detect airplanes, boats or submarines." Frank said that he could not hear his eyes blinking because they did not vibrate fast enough. On clarification he explained that the sound of an eye blinking was infrasonic, too low pitched to be heard.

On the prior questions Frank's conceptualization of frequency ranges approached the *scientific* perspective but was incomplete. He said correctly that ultrasonic sounds were too high pitched to be heard and provided two uses for ultrasonic sounds. Although he did not use the terms audible range or infrasonic range, he knew that humans were unable to hear sounds that were too high or low pitched.

On the midpoint sound test Frank had a *scientific* conceptualization of frequency ranges. He listed correctly the frequencies he could hear and labelled them "audible sound." He identified both the definition and an example of infrasonic sound. He gave several correct uses of ultrasonic sounds including sonar which he mentioned in his description of echolocation.

On the final questions Frank had a *scientific* conceptualization of frequency ranges. He provided a correct definition and several applications of ultrasonic sound. He listed the frequencies he could hear and labelled them "audible range." His explanation that we cannot hear an eye blinking "because it vibrates too slowly" indicated that he knew that infrasonic referred to sounds that were too low pitched to be heard.

4.4.3.3 Transmission of Sound -- via particle collisions and through the states of matter

On the prior questions, from a list of possibilities (like a baseball being thrown from one place to another; like the form of heat transfer called conduction; like the form of heat transfer called convection; like sunlight passing from the sun to earth; or something else) Frank selected *like the form of heat transfer called conduction* as the process most similar to sound transmission. He said that when the bat hit the ball "the particles move and make a noise and that makes other particles make noise." Frank said that in a liquid the particles were able to move so it was possible to hear sounds underwater. In his diagram of how the sound of howling wolves reached the tent, he drew dots that represented particles. He sketched a series of particles colliding in a chain reaction so that the sound moved in a *zig-zag* path. He said "that the particles hit each other to make noise, and when particles hit other particles they transfer sound." Frank said that sound could not pass through empty space because "it needs particles to hit and rebound off of." He thought that sound could travel through all states of matter and added that sound travelled "best through solids, second best in liquids and worst in gases." He said that the speed of sound depended on the "density" of the particles. His description of density referred to how tightly the particles were packed. He added that sound travelled fastest in solids because "the particles in solids vibrate quicker [than in liquids and gases]." On clarification, he said that in solids the particles were close together so the series of collisions with neighbouring particles occurred quickly.

On the midpoint sound test Frank identified conduction as a method of heat transfer most similar to the transmission of sound because the particles had to "vibrate and smash into each other." For the scene in which a spaceship was hit by a missile and the sound of the explosion was heard shortly after, he said there was nothing wrong because "the sound of the explosion would take time to travel to the camera." During probing he said that light travelled faster than sound. He thought that sound did not travel in the form of *sound particles* because "sound needs real particles to travel." On clarification, he said that as long as there were particles, sound could pass through. He said it was possible to hear underwater because "there were particles in water that collided and vibrated."

On the midpoint sound test Frank faced a problem. It was suggested that sound should pass through gases faster than through solids which is the reverse of what is observed in nature. He said the description of sound transmission was not correct because for sound to travel it required particles that "could bump into each other." He explained that the faster the particles hit one another, the faster the sound travelled, and sound travelled fastest in solids. In his diagram of the sound of a loud car entering a classroom, Frank drew circular lines (which he identified as sound waves) spreading out from the car until they reached the wall. Within these lines he drew dots representing particles. He said the "sound waves spread out and some of them go through the open space and into my ear." He added that the particles were vibrating against each other. In his sketch of how the car's sound travelled into a classroom when the window was closed he drew sound waves spreading out. He also included some sound waves reflecting off the wall. Near the sound source he said there were "loud sound waves" and beyond the classroom wall he said there were "soft [quiet] sound waves." He said some of the sound was absorbed and passed through the wall and into his ear, but most of the sound rebounded off the wall.

On the final questions Frank said that heat conduction and sound transmission were similar because both made particles move and passed fastest through solids and slowest through gases. He said that if he were on the moon he would not hear the impact of an asteroid on the other side because there were no particles to vibrate on the moon. On clarification, he explained that when he said there were "no particles" he was referring to the absence of an atmosphere around the moon. He said that you would be able to hear the sound of rocks banging underwater because "water has particles that can vibrate too." He argued that *sound particles* did not exist because sound was not produced in a vacuum. On clarification, Frank said that "if *sound particles* existed they should have been able to pass through empty space, but sound transmission does not occur that way."

On the final questions Frank faced a problem about the transmission of sound accompanied by three diagrams showing how sound would travel through a solid, a liquid, and a gas. It was suggested that sound should travel fastest through gases because there were large enough gaps between the particles to allow sound to pass through easily and that sound could not pass through a solid because the particles were *locked together* without any gaps to allow the sound to pass though. Frank said the theory was incorrect because sound passed through solids faster than liquids and gases. He explained that sound travelled faster through solids because the particles were close together and bumped into each other rapidly. In his diagram of sound transmission from a tuning fork he drew vertical bands of dots representing particles in both compressions and rarefactions and showed the tynes of the tuning fork vibrating up and down. For the diagram of the motorcycle's noise entering a restaurant, Frank sketched a motorcycle and a person dining in the restaurant surrounded by many dots representing particles. He said "the particles vibrate and make other particles vibrate until it [the sound] reaches your ear." During probing he said he was trying to show the particles vibrating and colliding into other particles.

On the prior questions Frank had an incomplete conceptualization of sound transmission. He said correctly that sources of sound vibrated and that sound transmission required particle collisions. He knew that the particles did not travel with the sound, but transferred energy through collisions with neighbouring particles. His ideas about sound transmission fit the *scientific* perspective, but a limitation in his conceptualization was that he did not know the role of sound waves in sound transmission. Frank had a *scientific* conceptualization of sound transmission through the states of matter. He knew that sound could pass through all states of matter and not a vacuum. Further, he knew that sound could change speed and explained how the arrangement of the particles allowed sound to pass faster through solids than liquids and gases.

On the midpoint sound test Frank had a *scientific* conceptualization of sound transmission. A major change in his conceptualization was that he included sound waves in both his description and diagram of sound transmission. He knew that sources of sound vibrated to create a compressional wave. He explained how compressional waves created compressions and rarefactions and caused the particles to collide with each other in a chain reaction. He knew that *sound particles* did not exist and that the particles did not travel with the sound, but collided with neighbouring particles. His diagram of sound transmission in which he drew sound waves moving away from a sound source provided evidence that he knew that sound spread out in all directions. He said incorrectly that there was nothing wrong with the scene in which a spaceship was hit by a missile and the sound of the explosion was heard shortly after. He based his answer on light travelling faster than sound rather than sound's inability to pass through a vacuum, in this case outer space. Frank's argument against the idea that sound passed fastest through gases and slowest through liquids provided evidence that he had a *scientific* conceptualization of how sound passed through each state of matter. He described how the rate of sound transmission via particle collisions was affected by the spacings between the particles in each state. He knew that the closer the particles were to each other (as in solids), the faster the speed of sound. His answers fit the *scientific* ideas that sound: could pass through all states of matter (solids, liquids, gases); would change speed depending upon what it passed through; would generally travel fastest through solids because the particles were closer together; would generally travel slowest through gases because the particles were farther apart; and could not pass through a vacuum because there were no particles available to vibrate.

On the final questions Frank had a *scientific* conceptualization of sound transmission. He described sound transmission as a series of collisions between neighbouring particles that vibrate. He knew that *sound particles* did not exist. A limitation in Frank's conceptualization of sound transmission was his description of sound waves. Although in his diagram of a vibrating tuning fork he indicated that a compressional wave produced compressions and rarefactions, he did not explain how these regions were related to the particle collisions involved in sound transmission. Frank had a *scientific* conceptualization of sound transmission through the states of matter. He explained correctly how the speed of sound through each state of matter depended on the spacings between the particles. He knew that sound passed faster through a solid, slower through a gas, and could not pass through a vacuum.

4.4.3.4 Transmission of Sound -- waves

On the prior questions the only mention of sound waves was when Frank said he wanted "to find out if it was possible to wreck things with sound like blow up rock with sound waves." On the midpoint sound test Frank said the evidence that sound travelled in the form of waves was that the waves were altered by "changes in loudness and frequency." He was referring to how changes in the loudness and pitch of a sound affected the wave representations on an oscilloscope. Frank correctly identified the lowest pitched sound, quietest sound, and noise by their oscilloscope representations. He drew a wavy line with low peaks that were close together to show how a quiet, high frequency sound would appear on an oscilloscope. He said that one way for sound to travel around a corner was by sound waves bending. Frank said that sound travelled as a compressional wave and that an oscilloscope made sound waves look like transverse waves. In his diagram of how the sound of a loud car travelled into a classroom, Frank sketched circles that became progressively larger and labelled them "sound waves." To explain why the sound of a firecracker was much louder when it was set off only 1 metre away rather than 1 kilometre away, he said that "close up the particles were vibrating faster, but farther away the sound was spread out." On clarification, he said that "spreading out" meant the sound's energy had spread out.

On the final questions, to represent how a loud, low frequency sound would appear on an oscilloscope, Frank drew a curved line with large, spread out peaks and troughs. He explained that as a sound spread out it became quieter because "the energy [of the sound] covered more space." He drew a tuning fork surrounded by regions where the particles were close together which he labelled "compressions" and regions where the particles were farther apart which he labelled "rarefactions."

On the prior questions Frank had no conceptualization of sound waves apart from having heard of the term. He did not include *sound waves* in either his description or diagram of sound transmission.

On the midpoint sound test Frank had a *scientific* conceptualization of sound waves. He included sound waves in his description of sound transmission. He knew that sound travelled as a compressional wave not a transverse wave, and that sound waves spread out in all directions from a sound source. He explained correctly that sounds became quieter the farther they travelled because the sound waves had spread out so the sound's energy had spread out. He used two properties of waves (that they could bend around or reflect off objects) to explain how sound could pass around a corner. He correctly sketched and identified sounds based on their oscilloscope representations indicating that he could distinguish between how a sound's loudness and pitch were represented on an oscilloscope.

On the final questions Frank had an incomplete conceptualization of sound waves. His answers were less detailed than on the midpoint sound test. Although he recalled that sound waves could reflect off objects and that sound became quieter as the sound's energy spread out, he did not say that sound waves could bend around objects. He knew how an oscilloscope represented the loudness and frequency of a sound. Although his statements about sound waves were correct, he did not include sound waves in his discussion of sound transmission or in his diagram of sound travelling from a motorcycle into a restaurant. His explanation for how sound could be heard without seeing the source of the sound did not include that sound waves could bend around objects.

4.4.3.5 Transmission of Sound -- echoes

On the prior questions Frank said that it was possible for sound to travel around corners because "the moving particles could move other particles around corners." On clarification, he said the particles did not necessarily move in a straight line and that they could be pushed to the side by other particles. Frank said that echoes were quieter because some of the sound was absorbed by what they hit. On the prior questions he did not explain how echoes were created, but during probing he said that echoes were sounds that "bounced off something."

On the midpoint sound test Frank said that one way sound could travel around a corner was by bouncing off a wall and another way was for sound to bend after passing something. To explain how an echo occurred he said "the sound hits a wall and bounces back late enough so that you can tell the difference between your yell originally." He said an echo was quieter because the sound was absorbed in the wall and the sound was more spread out. Frank said that echolocation could be used for "finding stuff in the dark." During probing he explained that he was thinking of how a bat flew at night. He said echolocation involved "a high pitched squeal hitting something and bouncing back." In his diagram of the car engine's sound going towards the classroom he drew wavy lines rebounding off the walls of a classroom and labelled them "rebounded sounds."

On the final questions Frank said echoes were produced by sounds rebounding off a wall. He explained that echoes were quieter because some of the original sound was absorbed (by what the sound hit) and spread out. To explain how sound could reach him when the source of sound was out of sight, Frank said "the particles start to vibrate against one another and then they vibrate and so on, the sound can travel a long way." He did not include echoes in his diagram of sound travelling from a motorcycle into a restaurant.

On the prior questions Frank had a confused conceptualization of echoes. Initially, Frank did not explain how echoes were created. He explained that they were quieter because some of the sound was absorbed by what it hit, but he did not mention that the sound's energy had spread out by the time it returned to the source. His description of how sound travelled around corners was unique and sophisticated. He based his explanation on sound transmission via particle collisions. He said that the particles collided in such a way that they could push other particles around a corner. He did not mention echoes as a possible way that sound travelled around a corner and he did not describe echolocation or sonar on the prior questions.

On the midpoint sound test Frank had a *scientific* conceptualization of echoes. He described how an echo occurred and indicated that there was a difference in time between when a sound was produced and its echo was heard. He provided two correct reasons for why an echo was quieter than the original sound. He knew that some of the sound's energy was absorbed by what it hit and that the sound had time for its energy to spread out. He knew that echolocation was used to locate things and involved high pitched sounds and echoes.

On the final questions Frank had a *scientific* conceptualization of echoes. As on the sound test, he correctly described an echo as a rebounded sound and provided two correct reasons for why an echo was quieter than its original sound. He recalled that some energy was absorbed by the wall that the sound hit and that the sound's energy spread out as it travelled. He knew what sonar was used for and that sonar was an example of echolocation. During probing his description of sonar included the term ultrasonic sound and he stated that it took time for a sound to be sent and return as an echo. He did not include echoes in his description of sound transmission.

4.4.3.6 Transmission of Sound -- the speed of sound versus the speed of light

On the prior questions Frank said that light travelled faster than sound, "because when lightning strikes you see the light before you hear the thunder." On the midpoint sound test Frank correctly identified 340 m/s as the speed of sound through air and said that light travelled at 300 000 km/s. He said that lightning was seen before thunder was heard, "because light is faster than sound so the sound takes longer to get to you." On the final questions Frank said the airplane appeared to be ahead of its sound "because once the sound gets to you the plane is still moving and it gets in front of the sound." To measure the speed of sound, Frank suggested that one person could fire a starting gun and another person could stand a kilometre away with a stopwatch. He said the gun could be fired and the other person would time how long it took to hear the sound. On clarification, he said that light travelled faster than sound, that the person timing would see the smoke (from the gun) right away, but the sound would take time to travel one kilometre.

Throughout the study Frank had a *scientific* conceptualization of the relative speeds of sound and light. On the prior questions he knew that light travelled faster than sound because lightning appearing before thunder was heard. A limitation in his conceptualization was that he did not know the speed of sound or the speed of light. On the midpoint sound test not only did Frank know that light travelled faster than sound, he knew their respective speeds. As on the prior questions, he explained correctly that lightning was seen before thunder was heard because light travelled much faster than sound. On the final questions Frank knew that light travelled much faster than sound. The experiment he designed to measure the speed of sound depended on light travelling faster than sound. Further, he allowed sufficient distance so that the light's arrival could be distinguished from the sound's. To explain why an airplane appeared to be ahead of its sound, he discussed the relative speeds of the sound and the plane. He knew it would take time for the sound from the airplane to reach the ground and in that time the airplane would have moved forward, but he did not discuss the speed of light in his response.

4.4.3.7 Reception of Sound -- the ear's anatomy and physiology

On the prior questions Frank's ear diagram consisted of an ear (ear flap), which led to a tunnel and filter, then an eardrum (drawn as a drum) and finally to an unlabelled tube to the brain. He said "the particles move inside the ear and the brain reads the pitch and turns it into words or sound." He added that humans could not hear sounds that were too high pitched or low pitched.

Following instruction about the characteristics and transmission of sound, but prior to discussion of the ear, Frank's ear design consisted of an ear flap with two funnels which led to two eardrums and nerves connected to the brain. He explained that sound arrived at the ear flap and entered one of the two funnels. He said the bottom funnel collected background sounds and could close to eliminate unwanted sounds. Sound entering the top funnel would go to the eardrum and cause it to vibrate. Then nerves would "pick up the sound waves and take them to the brain" which would describe different pitches and loudness.

On the diagram of the ear provided on the midpoint ear quiz, Frank correctly labelled the ten indicated structures. He gave the following answers on the fill in the blank portion of the ear quiz: the part of the ear that was filled with fluid was the "cochlea"; the part of the ear that collects the sound was called the "ear flap"; the semi-circular canals helped control our sense of "balance"; the thin membrane that vibrates when hit by sounds was the "eardrum"; the "auditory nerve" was the name of the nerve that connected the ear to the brain; and the "middle ear" was the section of the ear that contained the hammer, anvil, and stirrup. He drew tiny hairs of different lengths in his sketch of a cochlea, and said "the long hairs detected low notes, the short hairs detected high notes, and the middle hairs detected moderate pitches". He said "the little hairs in your cochlea determine your audible range." He explained that the smallest hairs determined how high a sound could be detected and the longest hairs determined the lowest pitch that could be heard. He added that the cochlea was the size of a pea. He said some animals' hearing was different from humans "because they had larger and/or smaller nerve endings [than humans]." He said the sound of a whistle would be collected by the ear flap and go down the ear canal to the eardrum which would vibrate in response to the loudness. He added that the eardrum was connected to a little bone called the hammer which hit the anvil. In turn, the anvil moved the stirrup and vibrated the oval window. He said the sound "goes into the cochlea which detects the pitch...[and the sound] goes to the brain in the auditory nerve." Frank said the advantage of the eardrum being much larger than the oval window was that the size of the eardrum "allows it [eardrum] to be more exact on the loudness and so the oval window can fit in the cochlea."

On the final questions Frank drew a detailed sketch of the ear that included the *pinna* (ear flap), ear canal, eardrum, hammer, anvil, stirrup, oval window, cochlea, auditory nerve, and brain. He also included the eustachian tube, semicircular canals, and balance nerve. He said "the ear flap collects the sound, it goes down the ear canal and it makes the eardrum vibrate." He explained that the hammer was connected to the ear drum, the hammer hit the anvil, the anvil moved the stirrup, and the stirrup was connected to the oval window of the cochlea. He said the sound went into the cochlea which detected the pitch. The sound then passed through the auditory nerve to the brain. He said the function of the cochlea was to detect the pitch of a sound. He explained that the small hairs detected high pitched sounds and the long ones detected low pitched sounds.

On the prior questions Frank had a confused conceptualization of the ear's anatomy. His diagram was limited to an ear flap, eardrum, brain, and tunnel (which corresponded to the ear canal). He was not aware of other structures such as the ossicles, cochlea, and auditory nerve.

On the prior questions Frank had a confused conceptualization of the ear's physiology. Although he knew that sound entered the ear flap, his description of what happened to the sound in the ear was that the sound caused the "particles to move" and somehow the brain "turned it [the sound] into words or sound." He correctly indicated that the ear flap funneled sound toward the eardrum, but he did not describe the eardrum's role in hearing. He did not include the ossicles, cochlea, or auditory nerve in his diagram of the ear so he was unable to describe their functions in hearing.

Following instruction about the characteristics and transmission of sound, but prior to discussion of the ear, Frank had a confused conceptualization of the ear's anatomy and physiology. His sketch of an ear resembled the diagram he made on the prior questions with the addition of several nerve paths and a second eardrum. As on the prior questions, he correctly indicated that the ear flap funneled sound toward the eardrum. An advance in his conceptualization of the ear's physiology was that he knew the eardrum vibrated in resonse to the sound. Although he did not include an auditory nerve in his diagram, he included eleven parallel nerves and said they took the "waves" to the brain and the brain determined the sound's pitch and loudness. He did not include the ossicles, cochlea, or auditory nerve in his diagram of the ear so he was unable to describe their roles in hearing.

On the midpoint ear quiz Frank had a *scientific* conceptualization of the ear's anatomy and physiology. He correctly labelled the diagram of the ear provided on the quiz and he correctly sketched how an uncoiled cochlea would appear, including the appropriate lengths of the tiny hairs. He provided a thorough description of how sound passed from the outer ear to the brain. A development in his conceptualization of the ear's physiology was his description of the eardrum causing the hammer, anvil, and stirrup (the ossicles) to vibrate and transmit the vibrations to the oval window of the cochlea. Another change in his conceptualization was that he described how tiny hairs of different lengths in the cochlea detected different pitched sounds.

On the final questions Frank had a *scientific* conceptualization of the ear's anatomy and physiology. His diagram was complete and the structures were in the appropriate locations. As on the prior questions he included an ear flap, eardrum, and brain, but on the final questions he added an ear canal, hammer, anvil, stirrup, cochlea (including the oval window), and auditory nerve. His inclusion of the semicircular canals and balance nerve along with a eustachian tube indicated that he knew not just the ear's anatomy but also its position relative to other structures within the skull. His description of how sound passed from the outer ear to the brain was thorough and similar to his description on the ear quiz. In the correct order he described what happened to the sound as it passed through each part of the ear on its way to the brain.

4.4.4 Engine Breakdown

4.4.4.1 Reception of Sound -- causes of deafness

On the prior questions, Frank said that our sense of hearing was vital because it allowed us to communicate. He identified loud sounds and ear diseases as causes of deafness. He thought the main purpose of learning about sound and hearing was to be able to prevent deafness and learning about how we can communicate.

On the midpoint ear quiz Frank said the main cause of hearing damage was loud sounds which usually damage the cochlea hairs and could not be fixed. He added that loud sounds could burst the eardrum. He said that obstacles in the ear canal were another cause of deafness, but they would still allow sound through, just not as well. In terms of the effect of pressure changes on hearing, Frank said "the popping was the ear's way of relieving the pressure." He said that throat infections "could creep up the eustachian tube and infect the ear or fuse together the bones [of the middle ear]."

On the final questions when asked if he would be completely deaf should his ear became plugged with a large piece of chewing gum, Frank said "no, you would not be completely deaf because the sound can still get through the bubble gum, but it will be muffled." For the case where the ossicles were damaged, Frank said, "No, you cannot hear at all because you could not detect the loudness." He said that temporary deafness was usually produced in the middle or outer ear. He said this type of deafness can be fixed naturally or mechanically. He said that permanent deafness was usually in the ossicles or the cochlea which cannot be fixed.

On the prior questions Frank had a confused conceptualization of the causes of hearing loss. He thought correctly that loud noises were a cause of deafness. He also listed ear diseases as a cause of deafness, but could not provide a specific example. He could not describe how loud sounds or ear diseases damaged the ear in terms of what part of the ear they affected and the type of damage they would cause. His limitations were not surprising because he knew little about the ear's anatomy and physiology on the prior questions.

On the midpoint ear quiz Frank had a *scientific* conceptualization of causes of hearing loss. He demonstrated that he understood both the ear's anatomy and physiology. He knew that loud sounds were the major cause of hearing loss and that they permanently damaged the tiny hairs in the cochlea. He said that an obstruction in the ear canal was a cause of hearing loss that could be fixed and would probably not cause total deafness. He knew that changes in altitude caused pressure differences inside and outside the eardrum which pushed the eardrum in or out and made hearing difficult.

On the final questions Frank had a confused conceptualization of causes of hearing loss. He knew that if chewing gum plugged his left ear he would probably not be completely deaf in that ear because sound might pass through or around the obstruction. He said that if the ossicles were damaged he would not be able to detect the loudness of a sound. He did not realize that sound might reach the oval window of the cochlea through the bones of the skull. He did not list causes of hearing loss. He stated correctly that damage to the cochlea was permanent. He incorrectly said that damage to the ossicles was permanent. He did not know that damage to the ossicles could often be corrected.

4.4.5 Discussion of Frank's Journeys

Just as a drag racer concentrates to be ready for the green light, Frank was prepared to work and learn. During a drag race, the driver must be aware of his surroundings, when to shift gears and when to slow down. Similarly, Frank was able to make links between his prior ideas and what was taught so that he quickly developed *scientific* conceptualizations. Generally, Frank's prior ideas were similar to the *scientific* perspective. His other prior ideas tended to be incomplete rather than confused. In developing *scientific* conceptualizations Frank did not have to "extinguish" his prior ideas. Rather, he could retain his prior ideas and incorporate more details from the lessons.

Characteristics of Sound

	Prior Questions		Mid-point Sound Test		Final Questions
Frequency and Pitch	Δ	-->	Δ	-->	Δ
Frequency Ranges	Δ	-->	O	-->	Δ

Transmission of Sound

	Prior Questions		Mid-point Sound Test		Final Questions
Particle Collisions	Δ	-->	Δ	-->	Δ
States of Matter	Δ	-->	Δ	-->	Δ
Waves	-	-->	Δ	-->	Δ
Echoes	Δ	-->	□	-->	□
Sound vs Light	Δ	-->	O	-->	□

Reception of Sound -- The Ear: Structure and Function

	Prior Questions		Ear Diagram		Mid-point Ear Quiz		Final Questions
The Ear's Anatomy	Δ	-->	Δ	-->	O	-->	O
The Ear's Physiology	Δ	-->	Δ	-->	O	-->	O
Hearing Loss / Deafness	Δ	----------------		>	Δ	-->	Δ

Δ = confused conceptualization

□ = incomplete conceptualization

O = *scientific* conceptualization

- = no conceptualization (student provided no information about a particular concept)

Table 4.4: Jane's Sonic Journeys

4.5 Jane's Journeys: Highway and Byways

4.5.1 Jane's Background

Jane earned high "B's" in both the first and second terms. In the first term her marks on tests averaged 76% and her overall term mark was 83%. In the second term her marks on tests averaged 73% and her overall term mark was 84%. Her marks for homework and lab reports were higher than her test scores and elevated her term marks. She played the flute in the school band. Jane's strengths were her organization, her ability to complete and hand work in on time, and her motivation to earn high marks. I selected her to participate in the study because I thought she would complete all the activities making up this study. Also, she wrote clearly so I knew she would be able to explain her answers. While she was satisfied with her marks in science, she found much of the first half of the course confusing. She said she had to study before things made sense to her.

4.5.2 Introduction to Jane's Journeys

For all the sound topics Jane's prior ideas did not fit the *scientific* conceptualization. The changes in Jane's conceptualizations of sound topics tended to follow one of three routes. For certain topics Jane moved rapidly toward the *scientific* conceptualization (as if she were passing directly to a destination via a highway) and her ideas were closest to the *scientific* perspective on the midpoint questions. For other topics Jane moved slowly toward the scientific conceptualization (as if she were driving unhurriedly along a byway) and her ideas were closest to the *scientific* perspective on the final questions. For the remaining topics changes in Jane's conceptualizations fit a *dual journey*, meaning that for certain sub-concepts she quickly approached the *scientific* perspective (highway drive), but for other sub-concepts she gradually approached the *scientific* perspective or remained confused (byway drive).

4.5.3 Jane's Highway Drives

In terms of the "characteristics of sound" Jane's conceptualizations most rapidly approached the *scientific* perspective for the topic of frequency ranges. In relation to her understanding of the "transmission of sound" Jane's conceptualization of the relative speeds of sound and light developed fastest. For the "reception of sound" Jane's conceptualizations of the ear's anatomy and physiology quickly approached the *scientific* perspective.

4.5.3.1 Characteristics of Sound -- frequency ranges

On the prior questions Jane said that ultrasonic sounds could be used at "a movie theatre" and at "a recording agency." On clarification, she said that she thought that movie theatres and recording agencies used noise reduction systems that involved ultrasonic sounds. During probing she was unaware of the terms infrasonic and audible sound ranges.

On the midpoint sound test Jane listed "a dog whistle, an unborn baby, and sonar" as examples of uses of ultrasonic sounds. She said that a dog whistle produced an ultrasonic sound. In referring to "an unborn baby" she explained that ultrasonic sounds could be used to look at an unborn baby in a pregnant woman. Jane identified infrasonic sounds as too low to be heard by humans and said that earthquake waves were an example of infrasonic sound. She said that the frequencies she could hear were 20 Hz to 20 000 Hz and that sonar used ultrasonic sound.

On the final questions Jane defined ultrasonic sounds as above 20 000 Hz and she listed "a dog whistle, earthquakes and underground explosions" as examples. She said her audible range was 19 Hz to 20 000 Hz. She did not state that sonar used ultrasonic sound.

Jane's prior ideas about the audible, infrasonic and ultrasonic frequency ranges did not fit the *scientific* perspective. On the midpoint sound test Jane displayed the *scientific* conceptualization of the frequency ranges. She correctly identified a definition and example of infrasonic sound, and listed the frequencies she could hear. She provided three correct uses for ultrasonic sounds.

On the final questions Jane had a confused conceptualization of the frequency ranges. She listed correctly the frequencies (in hertz) associated with audible, ultrasonic and infrasonic sounds. She correctly cited the sound of a dog whistle as an example of an ultrasonic sound. Evidence of confusion appeared when instead of listing uses of ultrasonic sounds Jane provided two examples of infrasonic sounds (underground explosions and earthquakes) and did not describe sonar as an example of a use for ultrasonic sound.

4.5.3.2 Transmission of Sound -- the speed of sound versus the speed of light

On the prior questions Jane thought that light travelled faster than sound and supported her opinion by stating that "it takes a minute or two for the stereo to go on." On clarification, she explained that it took time for the sound to come but the lights on the stereo appeared immediately. She thought that the speed of sound could change. Her explanation of how sound could change speed was "you could change stations [on a stereo receiver]."

On the midpoint sound test Jane said that light travelled faster than sound so lightning was seen before thunder was heard. She identified the speed of sound through air as 340 m/s.

On the final questions, without being asked directly about the relative speeds of sound and light, Jane was to apply her knowledge to answer two questions. Jane thought that an airplane appeared to be ahead of its sound because the engines (the sound source) were at the back of the plane. During probing, she said it was an "obvious question." She said the reason the sound seemed to be behind the plane was "because most of the plane is ahead of the noisy engines." When asked directly about the relative speeds of sound and light, Jane said that sound travelled slower than light, but added that she could not remember their speeds. She provided a detailed description of how she would determine the speed of sound. She said that two people could stand far apart (one on a mountain and one at a golf course). One person could smash a bat against a rock and the other person could record the difference between the time of seeing the bat hitting the rock and hearing the sound to calculate the speed of sound.

Jane's prior ideas of the relative speeds of sound and light did not fit the *scientific* perspective. Although she answered correctly that light was faster than sound, the evidence on which she based her answer had no connection to the relative speeds of sound and light. Jane had observed that when she turned on her stereo the lights came on before sound was produced. She interpreted her observations as convincing evidence that light travelled faster than sound. On the midpoint sound test Jane had the *scientific* conceptualization of the relative speeds of sound and light. She correctly identified the speed of sound through air and she applied her knowledge of light travelling faster than sound to explain why lightning was seen before thunder was heard. On the final questions Jane had a confused conceptualization of the relative speeds of sound and light. Although she recalled that light travelled faster than sound, she did not remember their respective speeds. Jane had difficulty explaining why the airplane appeared ahead of its sound. She focused on the location of the engines at the back of the airplane, but did not include the relative speeds of sound and light in her explanation. In the second question on the determination of the speed of sound Jane devised a logical, detailed experiment that was based on light travelling faster than sound. In her designed experiment she did not state explicitly that light travelled faster than sound, but during probing she said that she knew that the person would see the bat hitting the rock before hearing it.

4.5.3.3 Reception of Sound -- the ear's anatomy and physiology

Jane's prior ideas of the ear consisted of two ear flaps and tubes that she labelled "tissue" leading to the brain in the centre of the head. She drew musical notes passing from the ear to the brain. She said that she had no idea of "what's in there." In her description of the ear detecting a sound she said that "sound passes through the tissue of the ear into the brain to give a message." Jane said that humans could not hear all sounds and added that "animals have better hearing because they are closer to the ground and that often makes a difference."

Following instruction about the characteristics and transmission of sound, but prior to discussion of the ear, Jane's ear design consisted of an ear flap which funnelled sound to the eardrum. The ear flap contained some ear wax and a filter to cut out unwanted sounds. Two channels led away from the eardrum, one to the brain and one to the other ear. There was a hexagon-shaped object that reflected incoming sound down one of the two channels.

On the midpoint ear quiz Jane correctly labelled the indicated ear structures on the diagram provided on the ear quiz. On the fill in the blank section of the quiz she said: the part of the ear that is filled with fluid is the "cochlea"; the part of the ear that collects the sound is called the "ear flap"; the semi-circular canals help control our sense of "balance"; the thin membrane that vibrates when hit by sounds is the "nerve fibre"; that the "auditory nerve" connects the ear to the brain; and the hammer, anvil, and stirrup are called the ossicles and are found in the "middle ear." Jane stated that "our ears determine our audible range and that animals had better hearing and poorer eyesight." For the sketch of the cochlea, she drew tiny hairs of different lengths and said that the long hairs detected low notes and the short ones detected high notes. She thought that the sound of a whistle passed "through the canal to the eardrum that vibrates, on to the hammer, anvil and stirrup, through the oval window into the cochlea which determined the pitch and finally reached the brain." She said that the eardrum's larger size than the oval window "allows the eardrum to collect more sound and amplifies the sound."

On the final questions Jane provided a detailed sketch of the ear. She included the following structures in the appropriate locations: ear flap, wax glands, ear canal, ear drum, ossicles, oval window, cochlea, auditory nerve, semi-circular canals, and balance nerve. She said that "the ear canal directs sounds, the eardrum vibrates, the ossicles make the noise louder, the cochlea detects sound and the semi-circular canals give balance." She sketched the cochlea and said it detected the pitch of a noise. She explained that the short hair in the cochlea detected high pitched noise, and the long hair detected low pitched noise.

On the prior questions Jane knew little about the ear's anatomy. Her initial ideas about the ear's structure were limited to ear flaps and tubes leading to the brain. Corresponding to her limited knowledge of the ear's anatomy, she knew little about the ear's physiology. She did not know what happened to a sound from the time it entered the ear until it reached the brain. Jane's idea was that the sound simply travelled to the brain which somehow made sense of the information. Following instruction about the characteristics and transmission of sound, but prior to discussion of the ear, Jane's conceptualizations of the ear's anatomy and physiology did not fit the *scientific* perspective. Her diagram of the ear resembled her sketch on the prior questions. The major change to her diagram was the addition of an eardrum, but she did not include structures such as the ossicles, cochlea, or auditory nerve. She provided more detail about what happened to the sound as it passed through the ear. She said correctly that the earflap funneled the sound to the eardrum and that the eardrum vibrated in response to the sound, but she added incorrectly that the eardrum filtered out unwanted noise. She was unaware of structures such as the ossicles and cochlea and thus it was not possible for her to describe their functions. On the midpoint ear quiz Jane had the *scientific* conceptualization of the ear's anatomy and physiology. She labelled the parts of the ear correctly on the diagram provided on the quiz. She answered the fill-in-the-blank questions of the ear quiz correctly, except for saying that the thin membrane that vibrated when hit by sound was a "nerve fibre" rather than the eardrum. She demonstrated that she understood what happened at each stage as the sound passed through the ear to the brain, including the role of the cochlea. Although Jane correctly described how the hairs in the cochlea determined the pitch of sound detected, she did not use this information to explain how an individual's audible range was determined. On the final questions Jane had the *scientific* conceptualization of the ear's anatomy and physiology. She produced a detailed sketch of the ear that consisted of all the parts discussed in class in the appropriate arrangement. She labelled the ear's structures correctly and also included accessory organs such as wax glands, semi-circular canals and a balance nerve. In point form she summarized what occurred in each part of the ear. She correctly described the function of the eardrum, and included that the ossicles amplified the sound. Jane recalled that the cochlea detected the pitch of the sound and correctly described the relationship between the length of the hairs in the cochlea and the pitch of sound the hair detected.

4.5.4 Jane's Byway Drives

Jane's conceptualizations of sound transmission *via particle collisions* and *through the states of matter* developed slowly, and most closely matched the *scientific* conceptualization on the final questions, and fit the journey of a byway drive.

4.5.4.1 Transmission of Sound -- via particle collisions and through the states of matter

On the prior questions from a list of possibilities for how sound travelled (like a baseball being thrown from one place to another; like the form of heat transfer called conduction; like the form of heat transfer called convection; like sunlight passing from the sun to earth; or something else) Jane selected *like a baseball being thrown from one place to another.* She added that sound "echoes all around as it goes to your ear." In her diagram of how the sound of howling wolves reached her, she said "the particles are moving" and that sound "echoes off mountains." Jane thought that sound travelled through all states of matter. She said, "when you talk on the phone the sound probably goes through all the states [of matter]." As an example of sound passing through a solid Jane said she could hear a teacher yelling in another room. She explained that if sound were loud enough, the solid wall would not reflect all of the sound, but some "would get through." She said it was possible for sound to pass through a liquid because she had heard sounds when she swam in a pool. Jane thought that sound could pass through a vacuum because when she listened through headphones "there is actually an empty space." On clarification she explained that she thought there was a vacuum between the headphones and her ears.

On the midpoint sound test Jane said that sound transmission was similar to heat conduction because both "travel as a group and can pass quickly through solids." For the situation in which a spaceship was hit by a missile and the sound of the explosion was heard shortly after she said the problem was that "in space there are no particles so you could not actually hear it." On clarification, she said "sound cannot travel without particles." She said it was possible to hear sound underwater because at the public pool she heard people talking or yelling even though she was underwater. Jane said that the *slinky demonstration* proved that "sound does not travel as *sound particles*, because the spring moves all at once instead of a bit at a time." She added that the coils were not able to move by themselves to the end of the slinky, but particles could move on their own. In imagining the students as air particles in a classroom with a sound passing through, Jane said that she and her classmates would travel "as a compressional wave from one side of the room to the other" and that she would move all the way across the room.

On the midpoint sound test Jane faced a problem. It was suggested that sound should pass through gases the fastest and solids the slowest which is the reverse of what is observed in nature. Jane said the description was wrong because it did not explain how the speed of sound changed in each state of matter. During probing, she said that sound went fastest through solids, but she could not remember why. Jane was asked to sketch, label and describe how the sound of a loud car reached her in a classroom when the window was open, and then when the window was closed. For the situation of an open window, she drew a series of vertical bands of dots leading from the car to the room and labelled the bands alternately as "compressions" and "rarefactions." The dots represented particles. The compressions appeared as narrow vertical bands of dots drawn close together. The rarefactions appeared as wider bands with greater separation between the dots. She said that the sound travelled in the form of waves to get through the open window. In the second diagram with the window closed, on both sides of the wall she drew vertical bands and labelled them "compressions" and "rarefactions." This time she drew the compressions as vertical lines and the rarefactions as wavy lines. (She said she was tired of drawing dots, so she represented the particles with wavy lines.) She did not draw any lines, dots, or waves in the wall, but she said that with the window closed "the sound must travel through the wall as a compressional wave." Jane said there would still be waves, but the wall "hurts" the sound quality. When asked to explain what she meant by the word "hurts," she said that the wall "made the sound quieter" but she did not know how.

On the final questions Jane said that heat conduction and sound transmission were similar because for each to occur the particles must bump into each other. She added that she remembered "particles bumping" from a discussion of the ear's physiology when it was mentioned that sound could pass through the bones of a skull. She said that no sound would be heard if an asteroid struck the other side of the moon because there were no particles on the moon. On clarification, she said on earth we could hear sounds because there is an atmosphere made of particles, but on the moon there is no atmosphere. She thought it would be possible to hear the rocks banging underwater because "the vibrations floated to the top like air bubbles."

On the final questions Jane faced a problem about the transmission of sound accompanied by three diagrams showing how sound would travel through a solid, a liquid, and a gas. It was suggested that sound should travel fastest through gases because there were big enough gaps between the particles to allow sound to pass through easily and that sound cannot pass through a solid because the particles were *locked together* without any gaps to allow the sound to pass though. Jane said the theory was wrong "because sound travels fastest through solids and the particles being close together allows the sound to pass straight through." She said "in solids the particles are so close to each other that if one moves the others do right away."

In her diagram of a vibrating tuning fork on the final questions she drew an alternating pattern of rings (representing compressions) and bands of dots (representing rarefactions). She included arrows radiating outward to show that the sound spread out in different directions. For her diagram of a motorcycle's sound reaching a person in a restaurant, she drew a motorcycle surrounded by circles representing sound waves that increased in size and moved into the restaurant. On clarification, she explained that the sound waves travelled into the restaurant bringing the *sound particles* with them. She said "because the motorcycle is so loud it is easy to carry the sound right to you. It may hit people, but it is able to reflect until it gets to you."

On the prior questions Jane thought incorrectly that *sound travelled like a baseball thrown from one place to another* and indicated that sound moved in only one direction, rather than spreading out in all directions. Her ideas about sound transmission were dominated by the concept of echoes. She thought that sound (a form of energy) travelled like a physical object that bounced off things as it travelled. She did not mention that sources of sound vibrated, that sound travelled in the form of waves, or that sound was transmitted by collisions between particles. Jane's conceptualization of how sound was transferred through each state of matter did not fit the *scientific* perspective. Based on her experiences, she said correctly that sound could pass through all states of matter but mistakenly thought that sound could pass through a vacuum. Although she said that sound could change speed her reason had no connection to how sound was transmitted through the states of matter. She could not explain how sound travelled in terms of sound waves or particle motion, and she made no link to how the arrangement of particles in each state affected the speed of sound.

On the midpoint sound test Jane knew that sources of sound vibrated, that sound transmission required particles and was similar to heat conduction, and that sound travelled in the form of a compressional wave. While these ideas fit the *scientific* perspective, she retained her initial ideas that the particles bounced off objects and travelled with the sound. Although she said that sound transmission did not involve *sound particles*, her description of herself as an air particle in a room with a sound passing through fit the idea of *sound particles*. In her diagram of sound transmission from a car into a classroom she sketched areas that she labelled correctly as compressions and rarefactions, but she did not mention particle collisions. As on the preview questions she thought correctly that sound could change speed as well as pass through all states of matter. Jane had a confused conceptualization of sound transmission through each state of matter. In a shift from her prior ideas Jane knew that sound could not pass through outer space (a vacuum) because sound transmission required particles. She knew that sound passed fastest through solids and slowest through gases, but could not explain how the arrangement of particles in each state affected the speed of sound. In sum, Jane knew that sound required particles. She recalled how the speed of sound varied in solids, liquids, and gases, but she could not explain sound transmission in terms of particle collisions or arrangement in each state.

Jane's conceptualization of sound transmission was closest to the *scientific* perspective on the final questions, but was confused. She recalled that sound transmission was similar to heat conduction and that sound travelled in the form of waves. In a major shift toward a *scientific* conceptualization, she said that sound transmission depended on particles bumping into each other. In her diagram of a motorcycle's sound entering a restaurant she indicated correctly that sound spread out in all directions from the source and she included compressions and rarefactions in her diagram of a vibrating tuning fork. On the final questions, as on the midpoint sound test, she remembered that sound required particles and could not pass through a vacuum. She explained that "in solids the particles are so close to each other that if one moves the others do right away." In describing how sound passed from water into air, Jane's description of vibrations floating up to the surface like air bubbles matched neither the *scientific* perspective nor her other descriptions of sound transmission on the final questions. She argued against the idea that sound passed fastest through gases because there were larger gaps between the particles. She applied the idea that sound transmission required particle collisions to explain why sound passed fastest through a solid. She explained that the different arrangements of the particles in a solid, liquid, and gas affected how rapidly the "particle vibrations" were transferred. On the final questions Jane provided correct answers and knew the terms to include in her answers (e.g. compressional wave, particles, heat conduction), but her description of sound transmission contained a major inconsistency. It was surprising that Jane believed simultaneously that *sound particles* existed and that sound passed fastest through solids because the idea of *sound particles* was consistent with sound passing slowest through solids because of the small gaps between the particles comprising solids. In sum, Jane knew that sound could pass through all states of matter via particle collisions, but could not pass through a vacuum. She explained correctly how the arrangement of particles affected the speed of sound through each state and why sound passed fastest through solids. Evidence of confusion was that she thought *sound particles* existed and that sound floated up through water.

4.5.5 Jane's Dual Journeys

Jane's conceptualizations of the remaining sound topics could not be categorized as only a *highway drive* or only a *byway drive*. Instead, Jane's ideas of these topics followed a dual journey. For some sub-concepts within each topic Jane rapidly approached the *scientific* conceptualization (*highway drives)* while for other sub-concepts Jane was confused on the midpoint questions and her ideas most closely fit the *scientific* perspective on the final questions (*byway drives).* Jane's conceptualizations split into two journeys for the following topics: "frequency and pitch" (under the heading "characteristics of sound"); "echoes" and "sound waves" (under the heading "transmission of sound"); "causes of hearing loss" (under the heading "reception of sound"). To illustrate a dual journey one topic, "frequency and pitch," will be presented.

4.5.5.1 Characteristics of Sound -- frequency and pitch

On the prior questions Jane thought that sounds differed in loudness but did not mention pitch. She described the noise at a hockey game as "yelling, clapping and echoes," and the mosquito's noise as "humming, buzzing and echoes." When asked to define the term pitch she said pitch indicated the loudness of a sound. She thought an amplifier would produce a higher pitched sound. For the situation in which an ambulance passed her with siren blaring Jane said the pitch would "change in a new territory due to mountains reflecting it." During probing, she explained that the loudness of the sound depended on how far away the ambulance was.

On the multiple choice section of the midpoint sound test Jane indicated that all sources of sound vibrate, long pipes make lower notes, and frequency is measured in hertz. On the short answer portion of the test she said that the higher the frequency the higher the pitch. To make a higher pitched guitar sound, Jane suggested shortening the string and using an amplifier. To alter the pitch of a drum she said "the number of vibrations of the drum must change," but did not say how she would cause the change. She defined vibration as "to move back and forth repeatedly." For a question based on the *frequency lab* Jane said that "the longer the rope [pendulum] the farther the weight had to go for one vibration so its frequency decreased."

On the final questions Jane said that as the frequency increased so did the pitch. To increase the pitch of a note on the flute she explained that "you could change the note [by changing the fingering] or blow harder." Jane said that the sounds we can hear "vibrate too fast to count" meaning that we could not observe individual vibrations. She said "the length of the string affected the frequency." She explained that a longer pendulum took more time to complete one round trip. For the situation in which the pitch increased as a drain pipe filled with water, Jane said that "the pitch changes because it hits water -- less water, different sound, more water, different sound." During probing, she said that she did not know why the pitch would increase.

On the prior questions Jane's conceptualization of frequency and pitch did not match the *scientific* perspective. She did not define the term frequency, mention the term vibration, or describe the relationship between the frequency and pitch of a sound. She thought that pitch described the loudness of a sound and that a *high* sound was a loud sound. Evidence that she used the terms pitch and loudness interchangeably was provided when she said that the pitch of an ambulance's siren increased as the ambulance approached because the sound became louder and that an amplifier could be used to increase the pitch of a sound (not the loudness).

On the midpoint sound test Jane had a confused conceptualization of frequency and pitch. Fitting the journey of a highway drive she correctly defined *frequency of vibration* and described the relationship between frequency and pitch. She also knew that as the length of a pendulum or stringed instrument increased, the frequency decreased. Her conceptualizations of pitch and loudness fit the journey of a byway drive. Although she correctly said that a guitar's pitch could be increased by using a shorter string, she incorrectly said that an amplifier would also increase the pitch. Her confusion in thinking that pitch and loudness described the same property of sound led to confusion when she applied her knowledge to alter the pitch of a musical instrument.

On the final questions Jane continued to have a confused conceptualization of frequency and pitch. She explained how the frequency determined the pitch of a sound. As a member of the school band Jane played the flute so she correctly described how to produce a higher pitched sound on a flute. She knew that most sound sources vibrated too quickly to allow the frequency to be measured easily and that a longer pendulum took longer to go back and forth so it had a lower frequency. Jane applied what she recalled about how the length affected the frequency of a pendulum to correctly answer that the short hairs of the cochlea detected high pitched sounds, but she could not explain why the pitch increased as a drainpipe filled with water. On the final questions Jane did not confuse pitch and loudness. However, she had difficulty applying what she knew about factors that affected the pitch of a sound to situations that had not been discussed in class.

4.5.6 Discussion of Jane's Journeys

I have categorized developments in Jane's conceptualizations of sound topics as fitting one of three types of journeys: a *highway drive;* a *byway drive;* or a combination of both journeys. The *highway drive* refers to concepts for which Jane approached the *scientific* conceptualization by the time of the midpoint questions. Fitting the journey of a highway drive, Jane quickly mastered the following sound topics: frequency ranges; the relative speeds of sound and light; and the ear's anatomy and physiololgy. For other sound topics, such as "frequency and pitch," she did not master the entire topic, but quickly mastered particular sub-concepts. The topics that Jane rapidly developed conceptualizations approaching the *scientific* perspective tended to involve memorization of facts in isolation such as definitions of sound vocabulary terms (e.g. frequency, ultrasonic sound, ossicles) or numbers (e.g. the frequencies making up the infrasonic, audible and ultrasonic sound ranges, or the speed of sound through air). Jane performed well on questions that required this type of memorization. Further, when Jane's observations of objects she could see matched the behaviour of sound she was more successful in memorizing those properties of sound. For example, during the frequency lab Jane determined that the shorter the pendulum the higher the frequency. She successfully applied this information to recall that the shorter hairs in the cochlea detected higher pitched sounds. The most dramatic examples of a *highway drive* for Jane's conceptualizations of the ear's anatomy and physiology in which she shifted rapidly from knowing little about the ear's structure and function on the preview questions to knowing the arrangement and roles of the parts of the ear on the midpoint ear quiz.

The *byway drive* refers to concepts for which Jane's conceptualizations most closely matched the *scientific* perspective on the final questions, indicating that she required more time to develop her ideas. Jane's conceptualizations of sound transmission "via particle collisions" and "through the states of matter" fit the journey of a byway drive. Concepts that Jane developed in the pattern of a *byway drive* tended to be either *abstract* [1] or interlinked with other concepts. Explanations of the behaviour of sound involving the application of several concepts simultaneously tended to require more time. Although knowledge production does not necessarily occur in a logical order, before Jane could develop a conceptualization that sound travelled in the form of sound waves, requiring particle collisions, she had to know about the concepts of sound waves, that sound required particles, and how sound affected the particles it passed through. After examining Jane's initial ideas about sound transmission, it was not surprising that she took time to develop her conceptualization of sound transmission and that she exhibited confusion during her journey.

Frequency and Pitch

	Prior Questions		Mid-point Sound Test		Final Questions
Jane	Δ	-->	Δ	-->	Δ
Bill	Δ	-->	Δ	-->	Δ
Mary	Δ	-->	Δ	-->	Δ
Frank	Δ	-->	O	-->	O

Frequency Ranges

	Prior Questions		Mid-point Sound Test		Final Questions
Jane	Δ	-->	O	-->	Δ
Bill	Δ	-->	O	-->	O
Mary	Δ	-->	Δ	-->	□
Frank	□	-->	O	-->	O

Legend

Δ = confused conceptualization

□ = incomplete conceptualization

O = *scientific* conceptualization

- = no conceptualization (student provided no information about a particular concept)

Table 4.5: Comparison of Student's Conceptualizations of the Characteristics of Sound

Particle Collisions		Prior Questions		Mid-point Sound Test		Final Questions
	Jane	Δ	-->	Δ	-->	Δ
	Bill	Δ	-->	□	-->	Δ
	Mary	Δ	-->	Δ	-->	Δ
	Frank	□	-->	O	-->	O

States of Matter		Prior Questions		Mid-point Sound Test		Final Questions
	Jane	Δ	-->	Δ	-->	Δ
	Bill	Δ	-->	O	-->	O
	Mary	Δ	-->	Δ	-->	Δ
	Frank	O	-->	O	-->	O

Waves		Prior Questions		Mid-point Sound Test		Final Questions
	Jane	-	-->	Δ	-->	Δ
	Bill	Δ	-->	Δ	-->	Δ
	Mary	-	-->	Δ	-->	Δ
	Frank	-	-->	O	-->	□

Echoes		Prior Questions		Mid-point Sound Test		Final Questions
	Jane	Δ	-->	□	-->	□
	Bill	Δ	-->	O	-->	O
	Mary	Δ	-->	Δ	-->	Δ
	Frank	Δ	-->	O	-->	O

Sound vs. Light		Prior Questions		Mid-point Sound Test		Final Questions
	Jane	Δ	-->	O	-->	□
	Bill	O	-->	O	-->	□
	Mary	Δ	-->	Δ	-->	Δ
	Frank	□	-->	O	-->	O

Table 4.6: Comparison of Student's Conceptualizations of the Transmission of Sound

The Ear's Anatomy	Prior Questions		Ear Diagram		Mid-point Ear Quiz		Final Questions
Jane	Δ	-->	Δ	-->	O	-->	O
Bill	Δ	-->	Δ	-->	O	-->	O
Mary	Δ	-->	Δ	-->	O	-->	O
Frank	Δ	-->	Δ	-->	O	-->	O

The Ear's Physiology	Prior Questions		Ear Diagram		Mid-point Ear Quiz		Final Questions
Jane	Δ	-->	Δ	-->	O	-->	O
Bill	Δ	-->	Δ	-->	Δ	-->	Δ
Mary	Δ	-->	Δ	-->	Δ	-->	Δ
Frank	Δ	-->	Δ	-->	O	-->	O

Hearing Loss / Deafness	Prior Questions		Ear Diagram		Mid-point Ear Quiz		Final Questions
Jane	Δ	----------------------		>	Δ	-->	Δ
Bill	Δ	----------------------		>	O	-->	Δ
Mary	Δ	----------------------		>	Δ	-->	Δ
Frank	Δ	----------------------		>	O	-->	Δ

Table 4.7: Comparison of Student's Conceptualizations of the Ear's Anatomy and Physiology

4.6 Gunstone's summary of the findings of conceptualization research

The charts on the preceding pages provide convenient references for the comparisons of the students' conceptualizations at each stage of the study. Following the first level of analysis, characterizing the four students' ideas as sonic journeys, the four students' conceptualizations of sound and hearing are compared with each other in terms of Gunstone's work. Gunstone (1988) used four headings to summarize the findings of research into students' conceptualizations: 1) students' prior ideas are different from *scientific* explanations; 2) students' prior ideas are often unaffected by instruction; 3) students hold ideas in common; and 4) students can hold prior ideas and *scientific* explanations simultaneously.

4.6.1 Students' ideas are different from scientific explanations

The study of the four students' conceptualizations of sound provided many instances in which the students' prior ideas differed from the ideas taught in the researcher's science class. Mary thought that ultrasonic sounds were louder sounds. She thought that the speed of sound was a constant and that sound travelled faster than light. To explain how sound transmission occurred she selected *like a baseball being thrown from one place to another* and said that sound could pass through a vacuum. Bill thought that ultrasonic sounds travelled too fast to be heard. To explain sound transmission he wrote "like hitting a gong on one side of a room and a gong on the other side of the room vibrates" perhaps describing a *resonance* effect. He also thought that sound rebounded off objects as it travelled. Jane thought that light travelled faster than sound because the lights on her stereo appeared immediately, but it took longer for the sound to be heard. She also said that sound could pass through a vacuum because "when you listen through earphones it is actually an empty space [meaning that sound can pass through headphones which contain empty space (a vacuum)]." Jane thought that animals had better hearing than humans because the animals were closer to the ground. Initially, all four students knew little about the ear's anatomy (apart from the ear flap and the brain) and physiology.

However, the four students also had prior ideas of sound which were consistent with those taught in science class and consistent with scientific explanations. All four students knew that an echo was produced when a sound reflected off an object. Frank, Mary and Bill knew that sources of sound vibrated. Frank, Jane and Bill said that light travelled faster than sound.

This study showed that: all four students had prior ideas which fit the *scientific* perspective; all four students had prior ideas which did not match the *scientific* perspective; most of Frank's prior ideas fit the *scientific* perspective; Jane's and Bill's prior ideas varied between diverging from and fitting the *scientific* perspective; and Mary's prior ideas did not fit the *scientific* perspective.

4.6.2 Students' prior ideas are unaffected by instruction

In this study there were instances when the students' ideas about sound seemed unaffected by the formal instruction. The study provided evidence that Mary's prior ideas were often unaffected by the lessons on sound and hearing. On the final questions many of her answers which diverged from the *scientific* perspective were similar to her prior ideas. Throughout the study Mary stated correctly that sound "expands" (spreads out), but she was unable to describe sound transmission in terms of particle collisions. Initially, she thought that sound travelled *like a baseball being thrown from one place to another.* On the midpoint and final questions, she agreed with the idea of *sound particles* presented in the questions. She thought that sound was carried in the form of *sound particles,* much like an object being thrown across a room. Mary's experiences with echoes in a tunnel convinced her that echoes were not quieter than the original sound. She thought this in spite of what was presented in class related to echoes. Over the time of this present study her belief that echoes were louder than the original sound was unshakable. Throughout the study Mary could not describe the ear's physiology beyond stating that a sound arrives at the ear and the brain "says you have a sound."

Bill's prior ideas about frequency and loudness dominated his conceptualization of the characteristics of sound later in the study. On the prior questions Bill thought that pitch and loudness described the same property of sound. In spite of the classroom instruction, Bill continued to use the terms loudness and pitch interchangeably on the midpoint test and final questions.

There was also evidence that the students' conceptualizations of sound and hearing were affected by the lessons. Bill and Jane had confused prior conceptualizations of the ultrasonic, audible and infrasonic frequency ranges, but by the midpoint sound test they developed *scientific* conceptualizations. Similarly Frank initially had a confused conceptualization of echoes, but demonstrated a *scientific* conceptualization on the midpoint sound test and final questions. All four students changed from confused conceptualizations of the ear's anatomy on the prior questions to *scientific* conceptualization on the final questions. When the four students' prior ideas differed from the *scientific* perspective, Frank, Jane and Bill developed *scientific* conceptualizations more readily than Mary.

4.6.3 Students hold ideas in common

The study found that the students' held ideas in common, some of which were *scientific* and others which were not. On the prior questions Frank, Jane and Bill wrote correctly that light travelled faster than sound. Frank, Mary and Bill correctly used the term "vibration" in their description of sound sources. Mary and Jane incorrectly thought that sound travelled like an object being thrown. Mary, Bill and Jane thought that echoes played a key role in how sound travelled and included echoes in their diagrams of sound transmission. Mary, Bill and Jane used the terms loudness and pitch interchangeably. Many other instances of student ideas held in common about sound are documented in this study.

4.6.4 Students' can hold prior ideas and *scientific* explanations simultaneously

It is difficult to address Gunstone's fourth point, that students can simultaneously hold the scientist's interpretation together with a conflicting view and use the scientists' interpretation in the classroom and the conflicting view in everyday life. In this study of four students' conceptualizations of sound, all the students' responses were generated in science class on tests or worksheets. No attempt was made to assess their responses outside the science classroom in a more *natural* setting. However, there were instances in which the students provided conflicting responses to different questions about the same concept, which indicated that the students held more than one view about a particular sound topic. On the final questions Jane correctly compared the transmission of sound with the conduction of heat because both processes involved "particle collisions." She knew that sound could pass through all states of matter. Yet on other questions she said that *sound particles* existed. In a diagram she indicated that *sound particles* travelled fastest through solids "because they are all together and because there is a path that is straight through the wall." Further she said that the sound of two rocks banging together underwater could be heard "because they [sounds] vibrate and float to the top."

The findings of this study are consistent with the literature on student conceptualizations of science phenomena and are consistent with the four points made by Gunstone. Students have prior ideas which are different from the ideas presented in science class and some of these ideas are unaffected by instruction. For the topic of the characteristics, transmission and reception of sound, students held many prior ideas in common, both fitting and diverging from the *scientific* perspective. Students may use two explanations to explain an event, one idea fitting the *scientific* perspective, the other diverging from the *scientific* perspective. Often they will not notice any inconsistencies between their conflicting explanations.

4.7 Comparison of the students' sonic journeys

Upon comparing the four students' sonic journeys several statements may be made to highlight the differences between their journeys. Frank and Mary's sonic journeys were the easiest to characterize. In Frank's case, most of his prior ideas were close to the *scientific* perspective which meant his conceptual development was more a case of fine tuning than massive renovation. When his prior ideas did not fit a *scientific* conceptualization it tended to be a case of omission rather than confusion. For example, he knew little about sound waves on the prior questions. As he learned about sound waves during classroom instruction he did not have to eliminate incorrect prior ideas, but incorporate what was taught into his existing ideas of sound transmission. In Mary's case, most of her prior ideas were far from the *scientific* perspective. The reason for representing her sonic journeys as *Orienteering without a compass* was to show the difficulties she had in forming coherent conceptualizations (from a *scientific* perspective) of sound characteristics, transmission, and reception. Many of Mary's difficulties appeared to stem from confusion when she could not directly observe the properties of sound. For example, she was not able to see the particle collisions involved in sound transmission so she relied on a description that involved sound moving from one place to another like a thrown object. In essence, when abstract explanations were provided for sound's properties, Mary resorted to her own concrete explanations which corresponded to her everyday observations of the world around her. Such was the case when based on her experiences with echoes in a tunnel she argued vigorously that echoes are louder than the original sound.

Although Jane's journeys and Bill's journeys may appear similar in that they developed *scientific* conceptualizations for approximately half of the sup-topics of sound and hearing, there were some significant differences. The differences in part arose from their different approaches to learning. Jane was a thorough, systematic student. She did well on questions which relied on memorization of facts and definitions of terms. She wanted to know the *right* answer so that she could learn it. Like Mary (but to a lesser degree), Jane had difficulty learning abstract explanations which were provided for sound's properties Bill was not as systematic as Jane. In some ways he was the reverse of Jane in that he did not like to memorize facts and he enjoyed discussion of the abstract explanations of sound's properties.

The most striking finding in analyzing the students' conceptualizations was that all four students' prior ideas had a powerful influence on their conceptualizations on the midpoint and final questions. In Frank's case the influence was advantageous, allowing him to broaden and develop his ideas. For Mary, her prior ideas created major problems as she could not move past her confusion to develop *scientific* conceptualizations. For particular sub-topics of sound and hearing Jane's and Bill's prior ideas were advantageous and for other sub-topics they were problematic.

Footnotes

[1] In relation to this study, the term *abstract* refers to the separation between the directly observable properties of sound and the explanations of those properties. For example an observable property is that sound can be heard around a corner. The term *sound waves* has been used to describe the transmission of sound, but sound waves are not directly observable. It has been observed that water waves can bend around objects. In creating an explanation of how sound travels around a corner the *abstraction* occurs when students are asked to transfer what they learned about the properties of water waves to explain the behaviour of sound in terms of sound waves.

CHAPTER V

CONCLUSIONS, IMPLICATIONS, AND RECOMMENDATIONS

5.1 Introduction

This chapter presents specific conclusions derived from the study of four students' conceptualizations of the characteristics, transmission, and reception of sound. A discussion follows in which: 1) the teacher-researcher's expectations are compared with how the students' conceptualizations actually developed during the study; 2) the study's findings are related to teaching practice in terms of the unit and lesson sequencing, the teacher demonstrations and student experiments, and the instruments selected for use in teaching the units on sound and hearing; and 3) the advantages and problems of having the dual role of teacher and researcher are presented. Following the discussion, implications for teaching practice are summarized along with recommendations for further research.

5.2 Specific Conclusions from the Study

The major finding in this study of students' conceptualizations was that the students' ideas were not static. The students' ideas changed as they moved through the lessons on sound and the ear's anatomy and physiology. These changes were chronicled in Chapter IV. In some cases the changes were minor, but particularly between the prior questions and midpoint questions many of the students' ideas changed significantly. Generally, the students included more details about particular topics on the midpoint sound test and ear quiz than on the prior questions. Much of the change was related to their use of vocabulary presented in class. The four students' conceptualizations developed in distinct patterns and tended to be strongly influenced by their prior ideas. As they made sense of the information presented in the lessons, elements of their prior ideas were found in their responses to the midpoint questions and the final questions.

5.3 Expectations Compared to Actual Experience

Prior to conducting the research, I made brief predictions as to how successful each student would be in generating *scientific* conceptualizations of sound and the ear's anatomy and physiology. The predictions were in large part based on the students' performances on tests in the first half of the Science 8 course. The predictions provided part of the basis that determined which students I selected for the study. I wanted to investigate students whose conceptualizations of sound and hearing would develop in different ways. The value of comparing my expectations of the students with how their conceptualizations actually developed was that it provided insights into how students think and learn rather than how the teacher believes they think and learn. The comparison provided information about what helped the students learn and what confused the students.

Many of the predictions were incorrect and the expectations of student performance were fulfilled in one instance only. In previous units in the Science 8 course Mary rarely did well on tests, averaging 61% in the first term and 53% in the second term. Many of the prior questions, midpoint questions, and final questions asked the students to apply their knowledge to situations not discussed in class which Mary had little success doing on previous unit tests. I had expected that Mary's prior ideas would not approach a *scientific* perspective. I expected her conceptualizations of sound to remain confused throughout the study which was the case. The major surprise, however, was her ability to demonstrate a *scientific* conceptualization of the ear's anatomy on the midpoint ear quiz and final questions.

Based on Frank's test results in the previous units I expected him to develop *scientific* conceptualizations of the sound topics by the midpoint and final questions. With the exception of *causes of hearing loss*, he did. I predicted, incorrectly, that Frank's prior ideas would differ greatly from the scientific perspective, particularly for the transmission of sound. He surprised me in that many of his prior ideas approached a *scientific* conceptualization. I was impressed that he knew that sound transmission required particle collisions, and that the speed of sound depended on the "density" of the particles (i.e. how tightly packed the particles were).

Throughout the study he had little difficulty understanding and applying what he knew about sound and utilizing new information as he developed his *scientific* conceptualizations of sound.

Before the study I viewed Jane as a *pragmatic* learner. I thought her strength was that she knew how to memorize information for tests. I expected that she would forget much of the information in a short period of time (a few days). Surprisingly, Jane's ideas on the final questions were similar to those on the midpoint questions. I was not surprised that she mastered the ear's anatomy because of her ability to memorize vocabulary terms and diagrams.

Based on Bill's performances on tests in the first two terms I expected his conceptualizations to be closest to the *scientific* perspective on the final questions as I thought that he was a reflective learner who required time to sort out his ideas. Bill was a careful interpreter of what he observed. He demonstrated his interpretive skills when he said that light could travel farther than sound because he could see stars from a far distance but not hear sound from as great a distance. Bill's conceptualizations approached the *scientific* perspective on the midpoint questions. I had expected Bill's conceptualizations to most closely approach the *scientfic* perspective on the final questions because I thought he would not have had sufficient time to develop *scientific* conceptualizations on the midpoint questions. I had expected Jane's conceptualizations to most closely approach the *scientfic* perspective on the midpoint questions because I thought she would quickly learn the material for the midpoint questions and forget much of the information by the time of the final questions, but the analysis of the data suggested that Jane's conceptualizations on the final questions were similar were similar to her ideas on the midpoint questions. Had I interchanged my expectations of Bill and Jane I would have more accurately predicted the developmental pattern of their conceptualizations of sound and hearing during the study.

Upon comparing my expectations of each student's ability to develop *scientific* conceptualizations with the actual conceptualizations they developed during the study, the major finding was that my expectations were often incorrect. I based my predictions mainly on the students' test results earlier in the Science 8 course. Although I could predict their test scores, I could not predict whether or not they would develop *scientific* conceptualizations for the characteristics, transmission, and reception of sound. The analysis of the four students' conceptualizations highlighted the fact that it is possible for students to do well on tests without having developed *scientific* conceptualizations of the information presented in class. To succeed on the tests the students may have relied on rote memorization to answer fill-in-the-blank and vocabulary matching questions. The use of open-ended questions, which required the students to think about situations involving sound that were not discussed in class, provided a clearer indication of whether the students had developed *scientific* conceptualizations. I had carefully selected students whom I thought would develop conceptualizations in different, specific ways during the study. While their patterns of conceptualization development differed, they did not differ in the ways I had expected. Based on this evidence, it would be unlikely that I could correctly predict how the conceptualizations of the other students in the class would develop.

5.4 The Study Related to Teaching Practice

Pedagogy encompasses many factors including the sequencing of the units and lessons. Underpinning the unit and lesson sequencing are the student laboratory experiments and teacher demonstrations selected to reinforce the ideas presented in class, and the methods used to evaluate student learning.

A unit on the characteristics and transmission of sound was followed by a unit on the ear's anatomy and physiology. The intent of sequencing the lessons in this way was to make it easier for the students to learn about the ear's anatomy and physiology, and at the same time reinforce what they had learned about the characteristics and transmission of sound. There was evidence that the students successfully developed *scientific* conceptualizations of various sub-topics of sound and hearing. The main positive effect of the sequencing of the lessons was that it appeared to make it easier for the students to develop *scientific* conceptualizations of the ear's anatomy and physiology. In spite of this evidence, a strong claim cannot be made that placing the unit on the characteristics and transmission of sound before the unit on the ear's anatomy and physiology was a critical factor in the students' development of *scientific* conceptualizations. Before such a claim can be made, the development of students' conceptualizations would have to be investigated as the students experienced a different sequencing of lessons. A question which remains unanswered was whether the students recognized the logic of the lesson sequencing (that one lesson was intended to build on the preceding lessons) or whether the students viewed the lessons as isolated and unrelated.

Integral components of the lesson sequencing were the teacher demonstrations and student experiments used as part of this study. The demonstrations were intended to provide physical representations of abstract explanations of sound's properties. The positive aspects of the demonstrations were that they illustrated particular explanations for the behaviour of sound and were convincing to the students. Often, the students cited the demonstrations in their answers to questions.

However, the demonstrations also created problems for some of the students' conceptualizations of sound and hearing. Often the students' interpretations of the demonstrations were too literal. The students did not recognize the limitations of the demonstrations, particularly the ripple tank and vacuum pump demonstrations. The major concern I had in using the demonstrations was that the students accepted my explanations too readily of what they observed during the demonstrations. I had expected them to challenge my explanations and provide their own.

The instruments used for data gathering in this study were designed to encourage student response. If only traditional forms of evaluation (e.g. multiple choice and matching questions) had been used in this study, then it would have been difficult to gather sufficient information which would allow the students' conceptualizations of sound and hearing to be chronicled. On formal tests students often leave questions unanswered. They know that incorrect responses do not receive marks. Although the midpoint sound test included multiple choice questions, and the midpoint ear quiz included a fill-in-the-blank section, both the test and the quiz featured many open-ended questions. Similarly, the prior questions and the final questions consisted mainly of open-ended questions. For the latter two sets of questions, the students were informed that their mark would not be based on the *rightness* or *wrongness* of their answers, but instead be based on the degree to which they described and explained their responses. The main benefit was that the students answered most of the questions and provided details rather than one word responses. Thus it became possible to obtain information about and probe their conceptualizations of sound and hearing.

5.5 Role as Teacher-Researcher

My dual role as teacher-researcher in conducting this study of students' conceptualizations was both beneficial and problematic. A major benefit was that the selection of students for this study was simplified. By conducting the study half way through the year I could predict which students would complete the activites and likely develop their ideas in clearly distinct patterns. Another benefit was that I spent more time talking to the students, getting to know not only the students' ideas but also the students.

There were many difficulties created by my role as both teacher and researcher. To avoid the appearance of favouring certain students over others, I probed the ideas of all the students in the Science 8 class, not just the four selected for the study. Much class time was required to probe the students' ideas following the prior questions, midpoint questions, and final questions. Also, considerable time was needed to analyze the students' answers during the study to determine which responses required probing. Finding this time was difficult because of the other time demands placed on me as a teacher. A second problem was that it was difficult to separate my role as teacher from my role as researcher. For example, often during probing (in my role as researcher) an opportunity would arise in which a student would ask a particular question about a concept taught in class. Rather than providing an explanation (in my role as teacher) I had to maintain the focus on the student's ideas. I separated the times when I was teaching from the times when I was gathering data. Although this situation did not create problems in terms of data collection, it created conflict within me in that my primary responsibility was to teach students and I thought that during probing I was missing key opportunities to help the students learn. As a result, in my future teaching I plan to probe students' ideas and take advantage of those *teachable moments*, times when students are highly motivated to learn.

5.6 Implications for Teaching Practice

Although only four students' ideas were investigated in this study, several implications for teaching practice arose. Discussing a student's ideas individually will likely provide the teacher with greater insight into what the student thinks about a particular topic than only inspecting their test scores. The discussion may increase the students' motivation to learn because they will sense that the teacher is interested in their ideas. Further, the discussion will likely yield opportunities for the teacher to clarify the students' ideas and provide *scientific* explanations. Additionally, requiring students to compare their prior ideas with their ideas at the conclusion of a unit allows the students to see how their ideas have been influenced in class and what they have learned.

5.7 Recommendations for Further Research

Several recommendations for further research emerge. In the literature, few other studies of students' conceptualizations of sound were found. None of the studies investigated how students' conceptualizations changed during a series of lessons. Educators are concerned about student learning. Learning refers to a process in which students gain knowledge or understanding of a particular experience. To determine what students have learned it is necessary first to assess what they know before they begin a unit. In order to better understand the process of learning, studies might be conducted to investigate *how* students make sense of what is taught in class, and how their conceptualizations change as they proceed through units on other science topics.

Earlier, the significance of sequencing topics in a unit related to sound was discussed.

The question arises as to whether sequencing the units and lessons differently would cause a difference in student learning. For example, would following the unit on the ear's anatomy and physiology with the unit on the characteristics and transmission of sound increase or decrease the rate at which the students developed *scientific* conceptualizations? How might one develop a sequence which is appropriate for the students' logic in learning rather than the instructor's assumptions about student learning?

In this study it was noted that all the students developed *scientific* conceptualizations of the ear's anatomy. It appeared that the students were motivated to learn about human anatomy. Studies could be conducted which chronicled the changes in students' conceptualizations of other science topics which link to human anatomy. For example, the physics topic of light is often presented in conjunction with lessons about the anatomy and physiology of the eye. Studies could be conducted to investigate whether linking physics with biology helps students learn about physics and/or biology.

5.8 Summary

The conclusions and recommendations discussed in this chapter have highlighted the importance of sensitizing science educators to the different ways in which students learn about the information presented in class. Not only do students come to class with a wide range of prior ideas, their patterns of conceptualization development are difficult to predict. Teachers should not be in a race to cover the most curriculum. 'Real' learning is a reflective journey of *trying on* new ideas and requires time. For many concepts related to sound, most noticeably sound transmission, students needed time to reflect on their prior ideas (particularly when their prior ideas conflicted with the expected outcomes) and digest the ideas presented in class. Teaching should focus on the students' conceptualizations, helping the students become aware of their own ideas to give them the opportunity to recognize both what and how they think. Finally, discussing students' conceptualizations on an individual basis will likely provide the teacher with a better understanding of both the students' ideas and the students themselves, helping create an atmosphere of mutual interest in the classroom.

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APPENDIX 1

Lesson Plans and Data Gathering Schedule

A. **Sound Unit**

1. **"Sound: What You Know!" Questions**
(data gathering instrument for the characteristics, transmission, and reception of sound)

- Introduce topic of sound briefly (as another form of energy to be examined)

- Assign "Sound: What you Know!" worksheet
  - emphasize to the students that I am interested in what they already know (i.e. their own explanations), not on perfect *textbook* answers
  - due before the students leave class

- Students will bring in sound-making device for next class

2. Sound

- Introduction -- of what the two units will consist
  - Sound: properties of sound; representation of sound; uses of sound
  - Hearing: how humans hear / structure and function of the human ear

- Probe the students' responses to the initial worksheet
  --> return their original responses (after making photocopies)
  --> ask specific questions about their responses (clarification and probing)

- Objects that make noise and/or can be seen to vibrate
  - tooting horn (plastic)
  - tuning fork
  - vibrating ruler
  - mandolin string
  - oscillating spring + 200 g mass
  - strike a beaker with water
  - person speaking (feel throat -- vocal cords)
  - student demos (musical instruments)

What do these sounds have in common? make noise / vibrations
What differences do you notice in these sounds?
pitch, loudness, tone

- All sources of sound vibrate! (hit table with metrestick for emphasis)

- Introduce concept of frequency
  - vocabulary: vibration, frequency, pitch, hertz, Hz

- Prepare for the Frequency Lab
  - set up lab report

3. Frequency Lab
- factors affecting the frequency of a pendulum
- how this applies to sound production

4. • Complete Frequency Lab
   • Frequency worksheet
   • Sound Puzzlers (questions related to sound)

5. Transmission of Sound (Demonstrations + Fill in the blank notes sheets)
   - • slinky demonstration
     - - compressional waves vs. transverse waves
   - • tuning fork demonstration
     - - conduction of sound through different materials
       wood, air, metals
     - - speed of sound -- complete data table
   - • vacuum pump demonstration
     - - radio -- changes in loudness as sound is pumped out then allowed back in
     - - balloon -- one popped in class / the other popped in bell jar
   - • ripple tank demonstration
     - - sounds spread in all directions
     - - sounds bend when they pass an object
     - - straight waves --> circle waves as they pass through an opening
     - - sounds can pass through each other

   Address questions such as can sounds travel around corners? through walls? through each other? does sound travel like a baseball?

   Students fill in all blanks to form their notes

6. Frequency Ranges (Demo's + Fill in the Blank Notes Sheets)
   - • Oscilloscope: Wave Representation
     - - label parts; amplitude = peak height; wavelength corresponds to frequency
   - • Audiogenerator
     - - generate sounds of frequencies 20 - 100 000 Hz
     - - show on oscilloscope
   - • Microphone
     - - pure sounds (instruments, tuning forks) vs. noise
     - - variations in loudness
   - • Worksheet on factors that affect frequency and the frequency ranges

7. Representing Sound Waves
   - • Review wave representation from last class
   - • Questions from Science Probe 8 text

8. Chapter Review
   - • go over text questions
   - • key ideas review handout
   - • Sound Jeopardy (game)
     - - trivia questions asked about topics related to sound

9. **Midpoint "Sound Test"**
   (data gathering instrument for the characteristics of sound and the transmission of sound)

B. Hearing and the Human Ear

1. **"Designing an Ear"** -- in class assignment
(data gathering instrument for the reception of sound following instruction about sound, but prior to instruction about the ear's anatomy and physiology)
    • then discuss the answers to the Sound Test (which they completed in the previous period)

2. Students' Ideas / The Ear -- Scientists' Conception
    • Students describe their own sketches -- explain how they think ear works
        - discuss commonalities and differences
    • Sketch human ear on chalkboard and handout information about the human ear
    • Ear Worksheet

3. Audiogenerator demonstration
    • Determining audible range
        - link to the structure and function of the coclea
    Deafness
        • Causes
        - emphasize that loud sounds are the leading cause of hearing loss
        - show electron micrograph of tiny *hairs* of healthy cochlea and damaged cochlea

4. Review causes of deafness
Testing for hearing loss with a tuning fork
    - Weber Test
    - Rinne Test

5. **Midpoint "Ear Quiz"**
(data gathering instrument for the reception of sound)

C. Application of Knowledge of Sound and Hearing

1. Hearing Device Project
    • Handout of assignment requirements
    (2 periods, including library time)

D. Sound and Hearing

1. **Final Questions: Sound and Hearing Summary Questions**
(data gathering instrument for the characteristics, transmission, and reception of sound)

administered 2 weeks after the conclusion of the sound and hearing units
    - in the interim the students completed a major library assignment
        (separate from sound and hearing units)

APPENDIX 2

Prestudy Predictions for the Changes in the Students' Conceptualizations

Bill

I expect that most of Bill's prior ideas will be *confused.* I think that he will have many problems learning about the aspects of sound presented in class and that it will take time for him to learn. I think the topics of sound transmission (sound waves, particle collisions)and the ear's physiology will be particularly difficult for him. I predict that his ideas will likely be *best* on the final summary questions. I think that he will quickly learn the frequency ranges and the relative speeds of sound and light.

Mary

I expect that most of Mary's prior ideas will be *confused. I think that* she will have problems learning about all the aspects of sound presented in class, particularly sound transmission (sound waves, particle collisions), and the ear's physiology. I think that she may learn the frequency ranges and relative speeds of sound and light.

Frank

I think that Frank's prior ideas will be *confused,* but I expect that he will likely have few problems learning about sound and the ear's anatomy and physiology and quickly develop *scientific* conceptualizations of all the sound topics.

Jane

I think that Jane's prior ideas will be *confused.* I think she will quickly learn about the frequency ranges, relative speeds of sound, factors affecting frequency. Her experience in the band may help her understand how the frequency of an object can be changed. She will have greater difficulty learning about sound transmission. I expect that her ideas will be closest to the *scientific* perspective on the midpoint sound test and ear quiz, not on the final summary questions. I view Jane as a pragmatic learner who tends to learn quickly, memorize facts, and she will likely forget much of what she learned by the time of the final summary questions.

APPENDIX 3

Data Gathering Instuments With Bill's Responses to the Questions

Prior Questions:

"Sound: What You Know" questions

Midpoint Questions:

"Sound Test"

"Ear Design Assignment"

"Ear Quiz"

Final Questions:

"Sound and Hearing Summary Questions"

Bill's diagrams have been photocopied directly. Wherever possible Bill's answers to the questions have been photocopied directly. In certain instances, due to difficulties with the quality of the photocopying of Bill's responses to the questions, many of his answers are typed verbatim in italics directly on the data gathering instruments. {His spelling mistakes and grammatical errors were left the way he wrote them.}

Sound: What You Know!

Science 8
Mr. Webber

Full Name: ____________________
Block: ___

Answer directly on these sheets. Credit will be given for providing <u>your</u> best answers. Guess if you have to. Do <u>all</u> the questions!

<u>Sound</u>

1. What do you think all **sources of sound** have in common (apart from making noise)?

   They all travel in waves and vibrate in your ear or whatever they hit

2. You hear the roar of the crowd at a hockey game after the Boston Bruins have scored. What are all the ways the sound of the crowd roaring differs from the sound of a mosquito buzzing in your ear? (i.e. What are the different properties of sound?)

   Peoples vocal cords and the echo off the walls of a stadium

3. What does the **pitch** of a sound tell us about the sound?

   It tells us the deepness of a sound

4. What are several ways of producing a **higher pitched** sound on a guitar?

   Change the setting on the amplifier

5. What are **ultrasonic sounds**? Give two practical uses for ultrasonic sounds (if you can).

   Sound that moves so fast we can't hear it.

   To look at a baby in a mother's stomach

6. What determines how **loud** a sound is?

   how many deciballs it has

7. Which travels **<u>faster</u>**: **sound <u>or</u> light**? Explain how you know.

   Light because it could take a while for sound to reach your ear from a distance but light can get to your eyes from a distance

8. Does sound travel **at only one speed**, **<u>or</u>** can it **change speed**? Explain.

   No it goes at the same speed all the time

9. Can sound pass through empty space (a vacuum)? Why or why not? Explain.

   No because it has nothing to bounce off of

10. Can sounds travel through a solid wall? If so, how do they do it? If not, what does the wall do to the sound?

    No because the sound waves can bounce off the solid wall

11. Can sound travel through all states of matter: solid, liquid and gas? Explain how you know for each state.

Yes because for all states you can hear sound. Underwater you can hear it in a room you can hear it in the air your hear it

12. a. What most closely matches your conception of how sound travels: Circle your choice.

    i. like a baseball being thrown from one place to another.

    ii. like the form of heat transfer called conduction

    iii. like the form of heat transfer called convection

    iv. like sunlight passing from the sun to earth.

    v. something else (describe below)

    b. For your choice, provide a description of how the sound produced by a baseball player hitting the ball with a bat arrives at your ear.

like hitting a gong from one side of the room and the other one vibrates it bounces off the bat and into your ear

13. Can sound travel around corners? Explain how you know.

No. It bounces off something and travels to something else in a strait line

14. How are **echoes** produced and why are they quieter than the original source of the sound?

The sound you make bounces off say mountains and back to your ear. They are quieter because

15. You are standing on the side of Highway 1 near Laidlaw. An ambulance, with siren blaring, is rapidly approaching. It passes you and heads on to Chilliwack.

    a. How does the pitch of the siren change?

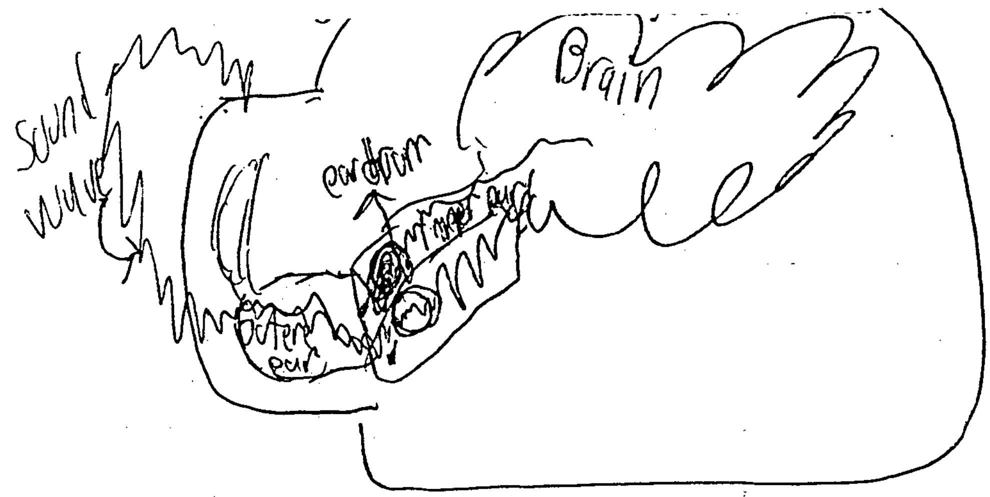
It goes from high to low

    b.What causes this change in pitch?

How close the ambulance is

The Ear / Hearing

1. a. Based on your present understanding of sound and hearing, make a **sketch** of what you think the inside of your ear looks like. (You do not have to include ear wax!)
Note: Your ear must somehow get the sound to your brain.
Focus on what each part does in relation to the various properties of sound.
LABEL YOUR DIAGRAM!!
Do not worry about getting *the right answer*. Just make your best effort.



b. How do your ears detect sounds? (i.e. How do they function?)

By vibrations to the ear drum

2. Can humans hear all sounds? What frequencies can you hear? (i.e. the range) Explain.

No, We can't hear a dog whistle.

3. Is it possible for you to hear sounds underwater when you are swimming? Explain. Assume your ears are functioning properly.

Yes because sound passes through water.

4. a. Explain how your sense of hearing is vital to your way of life.

You have to hear 18 wheelers coming down the highway so you don't get hit.

b. What are some causes of deafness? How does each damage the ear?

LOUD NOISE Like airplanes. It blows your eardrum.

c. What changes would you have to make in your everyday life if you became deaf?

I would never leave the house.

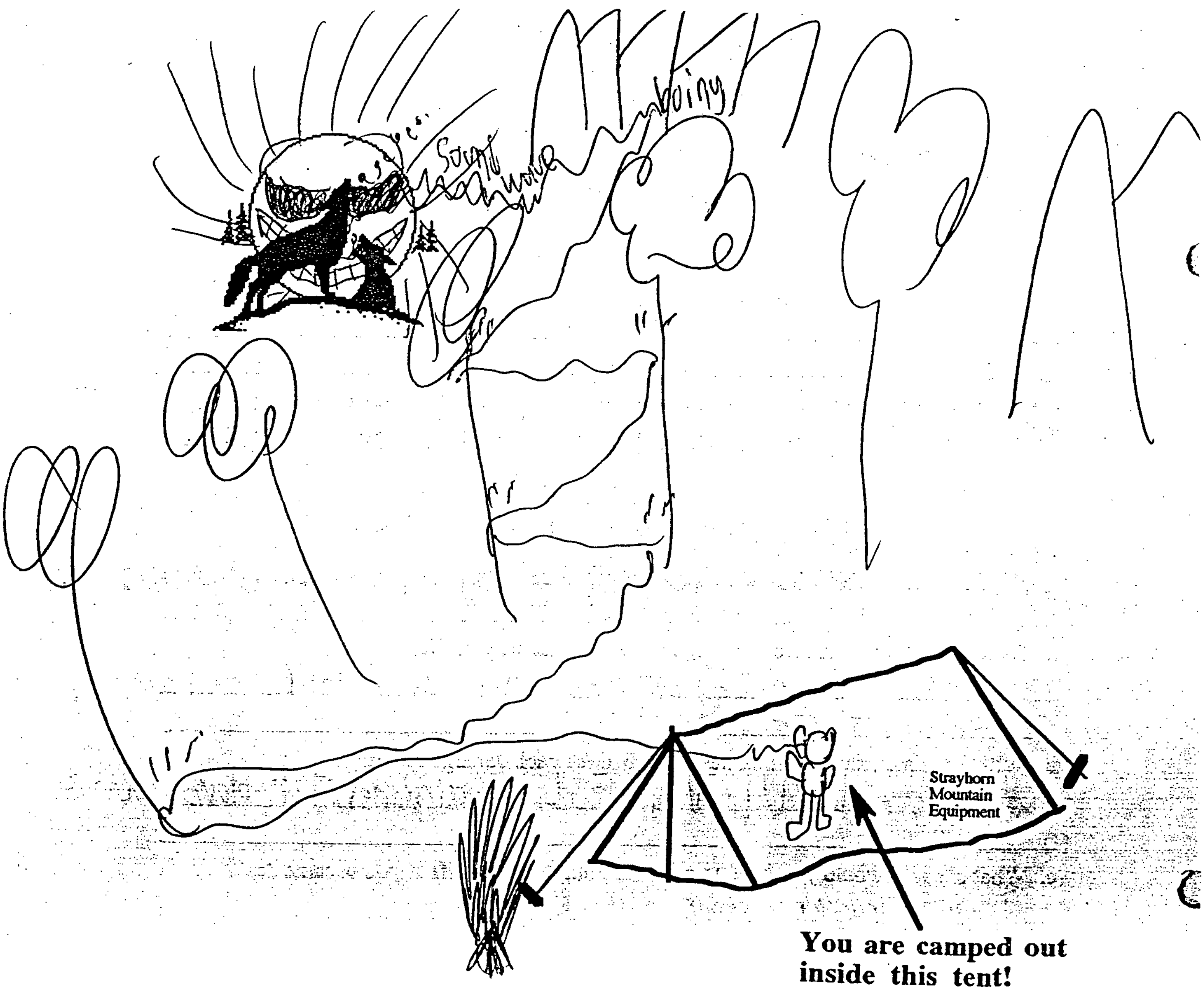
5. What are some reasons for learning more about sound and your sense of hearing?

So you can learn how to protect it

Quality Diagram Time

Pictured below are two wolves howling at the top of a ridge at midnight. On the diagram below sketch and label **how** the sound gets from the wolves to you as you rest in your tent below near a lake.

Refer to question 12 to help provide a detailed explanation. (i.e. What happens to the wolves, the air, the land, the trees, etc.?) You don't have to include all of these, but make sure your answer is detailed.



Sound Test

Science 8
Mr. Webber

76

Full Name: ________________
Block: A

Part 1: **Multiple Choice**

For each question, choose the **best** answer and place its corresponding letter in the space provided. Circle your choice -- just to be safe.

✓ d 1. All sources of sound:
a. produce noise
b. produce one frequency of sound
c. are stationary
d. vibrate

✓ a 2. Infrasonic sounds are:
a. too low to be heard by humans
b. heard by humans
c. used in echolocation
d. made on the planet Infra

✓ a 3. In rarefactions:
a. air particles are spread out
b. air particles are facted
c. sound cannot travel
d. air particles are squeezed together

✓ a 4. If the frequency increases, the pitch:
a. increases
b. decreases
c. stays the same
d. is sticky

✓ d 5. The frequency of an object:
a. is how high it swings
b. measures the object's length
c. cannot be changed
d. is the number of times it vibrates in one second

✓ d 6. A pipe organ has long pipes to produce:
a. louder sounds
b. quieter sounds
c. higher notes
d. lower notes

✓ d 7. This animal uses echolocation to fly and hunt in the dark:
a. crow
b. flying squirrel
c. hummingbird
d. bat

✓ a 8. Frequency is measured in:
a. Hertz
b. metres per second
c. dollars
d. calories

✓ c 9. The frequency at which an object moves back and forth is called:
a. high frequency
b. low vibration
c. natural frequency
d. normal frequency

✓ b 10. The speed of sound through air is approximately:
a. 100 km/h
b. 340 m/s
c. 300 000 km/s
d. 200 mph

✓ a 11. Sound tends to travel **fastest** through:
a. solids
b. liquids
c. gases
d. vacuum

✓ a 12. Earthquake waves are an example of this type of sound:
a. infrasonic sound
b. audible sound
c. ultrasonic sound
d. rock and roll

Part 2: **Short Answer / Fill in the Blank**

1. Explain how **pitch** and **frequency** are related. (2)

The higher frequency the higher pitch

The lower tfrequency the lower pitch

2. a. What form of **heat transfer** is sound transmission similar to? *conduction*
b. How are they similar? (2)

the both occur in all states of matter and they both occur fastes in solids because in solids the particles are locked together

c. In the ***Star Wars*** series of movies you would often see a spaceship struck by a missile, and shortly after you would hear the explosion. What is wrong with this scene? (2)

There is nothing wrong because light tis faster than sound so you would hear it a half second later .

3. Give three practical uses for **ultrasonic sounds**. (3)

pregancy baby checkers

kidney stone crushers

a dog whistle to call Fifi

4. a. Based on the demos in class, what evidence is there that sound **does not** travel in the **form of *sound particles*** ? (3)

The evidence is the ballon in the vacuum. We could not hear the balloon as nearly as well when it was outside the vacuum.

b. Based on the demos in class, what evidence is there that sound travels in the **form of *waves*** ? (3)

The evidence is that when we used the ripple tank.

5. What are **two** ways that sound can travel around corners? Describe them. (3)

One way is it can pinball off the walls and the other is it can bend around corners.

6. Explain why you will see the lightning **before** you hear the thunder. (2)

Because light moves way faster than sound light at 300 000 km/s moves way faster than sound at 340 m/s

7. Is it possible for you to hear sounds underwater when you are swimming? Explain why or why not. {Assume your ears are functioning properly.} (3)

Yes becase sound does not travel in the form of sound particles it can go through the state of water.

8. What frequencies can you hear? (i.e. the numbers) (2)

We can hear from 20 to 20 000 Hz

9. You are walking through the Othello Tunnels when you let out a yell. You hear an echo.

a. Explain how the echo occurs. (2)

The echo occurs by your sound waves rebounding of the rock walls and back to your ears.

b. Is the echo produced louder or quieter than the original sound (in this case the yell)? Explain why. (3)

It is quieter because the wall absorbs some of the energy and because the energy is spread out.

10. You're now a member of **REM** (music group).

a. What are **two** ways of producing a **higher pitched** sound on your guitar? (2)

You can pluck the strings harder or shorten the strings with your fingers.

b. How are drummers able to make different pitched sounds with their drum sets? (2)

By hitting the drums harder.

11. a. What does the term **vibration** mean? (2)

Vibration means something moving back and forth.

b. What was the purpose of the pendulum experiment we did at the start of this chapter? (2) (i.e. What connection did it have to sound?)

To see if the length of something effects it's sound.

c. In this experiment, what did you learn about how the length of the pendulum affects its frequency? (2)

Because when you lengthen it it bceomes louder.

12. Briefly explain how **echolocation** works and what it can be used for. (3)

Echolocating is when something makes a noise and see how long it takes the travel back to it. We can use it for stuff like sonar and stuff like that.

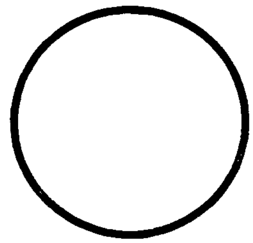
13. a. How does sound travel? Like a compressional wave or a transverse wave?

compressional

b. What evidence did the slinky demo provide to support your answer to part 'a'? (2)

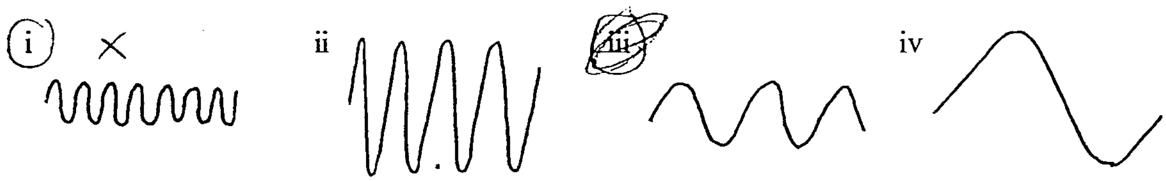
Because when you wiggled the slinky where the wave went it compressed together.

14. Sketch how a **quiet, high frequency** sound wave would appear on an oscilloscope. (2)

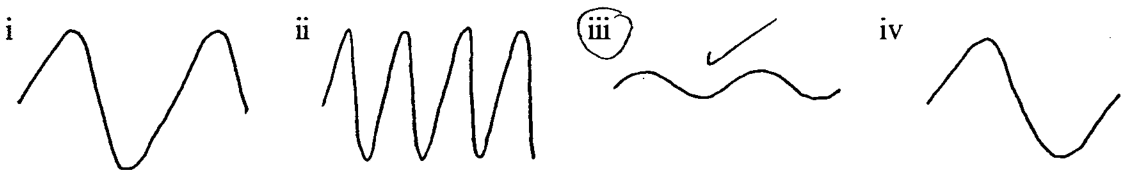


15. The following sketches show how each sound wave would be represented on an oscilloscope. Circle the appropriate sketch.

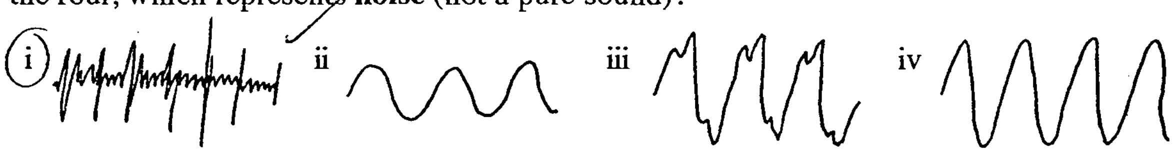
a. Of the four, which represents the **lowest pitched** sound?



b. Of the four, which represents the **quietest** sound?



c. Of the four, which represents **noise** (not a pure sound)?



16. What is ***misleading*** about how sounds are represented on an oscilloscope? (2)

Sound travels as a compressional wave. The oscilloscope shows it as a transverse wave.

17. Explain why a firecracker will sound much louder if it is set off 1 m away than if it is set off 1 km away. (3)

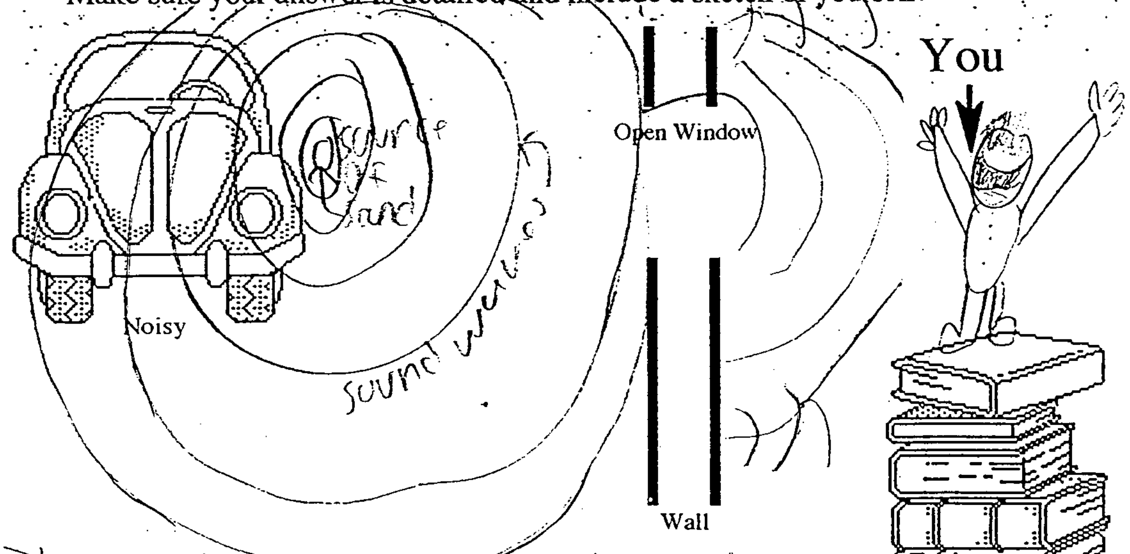
It will sound louder because sound traves in m/s rather than km/s.

18. Consider yourself to be an air particle and all your classmates are other air particles. Describe what would happen to you (if you were an air particle) as the sound passed from one side of the room to the other. (3)

I would start to vibrate bump into Iris make her vibrate she would bump into Fred make him vibrate and so on.

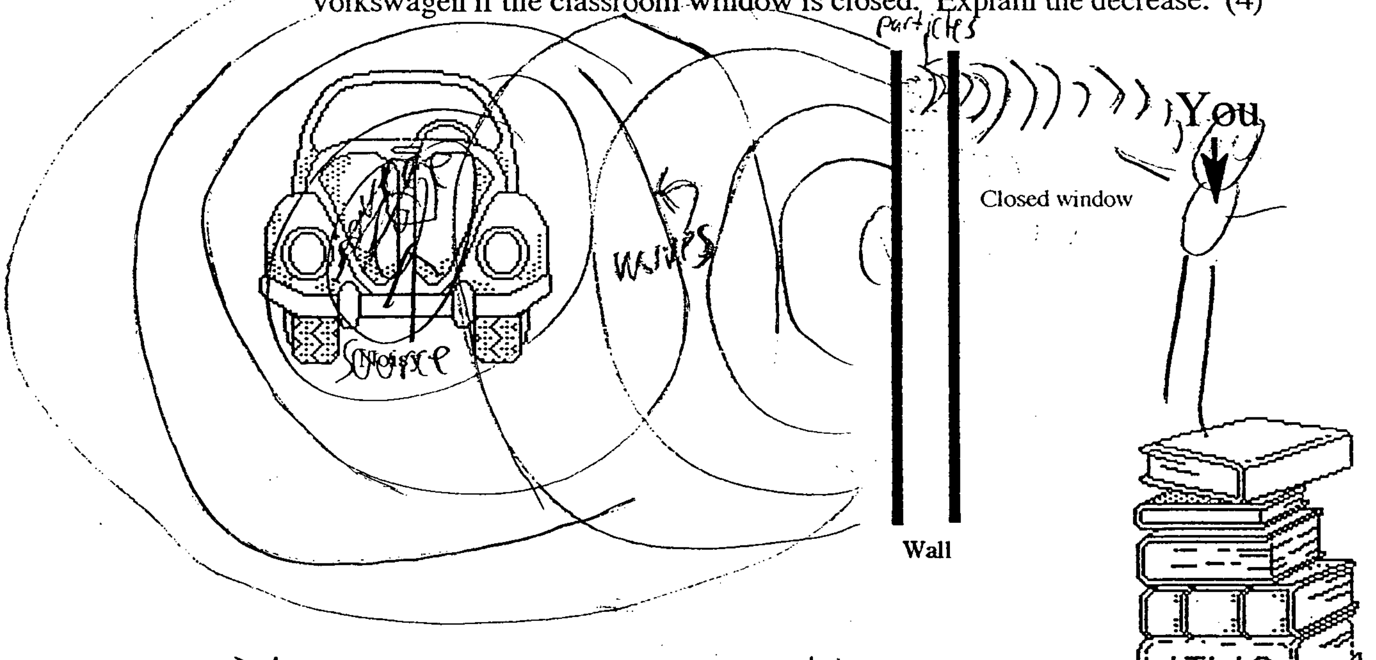
19. Old volkswagens are famous for their loud engines. The old volkswagen pictured below is rumbling by the school while you are in Social Studies.

a. Your job is to **<u>sketch, label and describe</u> how** the sound gets from the volkswagen to you as you work hard in your class with the window open. (6)
Make sure your answer is detailed and include a sketch of yourself.



The ~~sone~~ sound can go through an open window so the sound from the engine would go through the window and to ~~me~~ my ear

b. Make a labelled sketch to show what happens to decrease the sound that you hear of the volkswagen if the classroom window is closed. Explain the decrease. (4)



The sound would mostly bounce of the wall but some of it would seep through and to your ear

20. You probably have noticed that it is easier to walk along a sidewalk through air (a gas) than through a large pool filled with water (a liquid). This may be explained by the particles of a liquid being closer together than those of a gas so that there are more particles to ***push side*** as you walk through the water.

Does the description above also explain how the speed of sound changes in solids, liquids and gases? Explain. (4)
(i.e. Which state of matter does sound travel through the fastest and does this match the description of walking.)

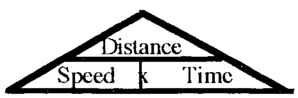
Yes because sound travels fastest in solids and we move the slowest in solids so it all matches up

Bonus

1. ***Echo calculation***

If Ry Cooder is boating 3150 m from the shore which consists of a tall vertical cliff, how long will it take from the time Ry plays the first note on his guitar until he hears the echo of that note?
Assume the original sound is sufficiently loud for him to hear the echo.
In this case, the speed of sound in air is 350 m/s.

T=D÷S
= 3150÷350



Answer: *4 seconds*

2. Why does sound travel farther on a cool day than on a warm day?
This is especially noticeable over calm water or a frozen lake.
The range of sounds in the desert, on the other hand may be noticeably limited.

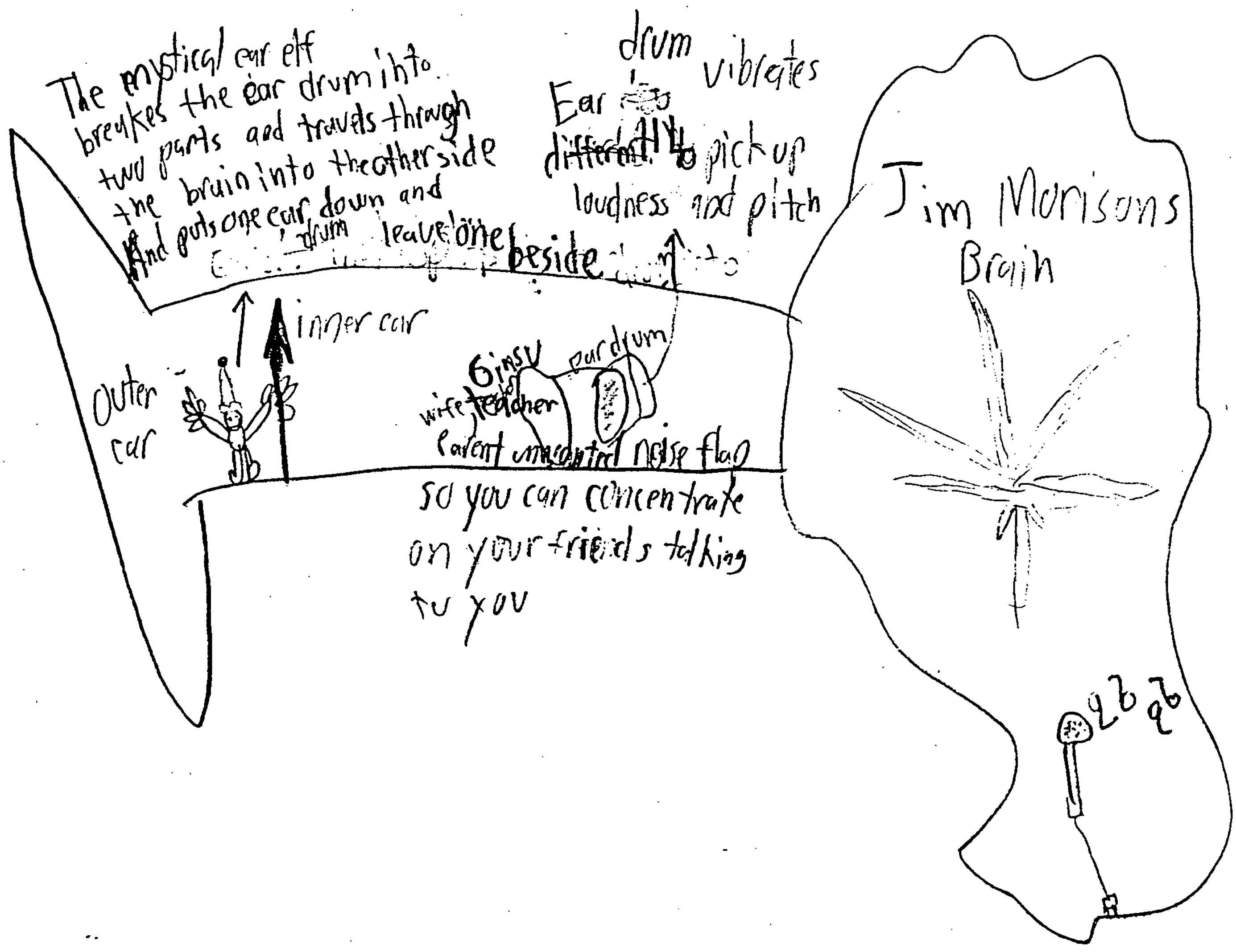
ON cold days the particles move slower than on warm days.

Ear Design Assignment

EAR'S 9US

_______________'s **Ear Design**

brought to you by Rockford land
a place where a kid can be a Adult



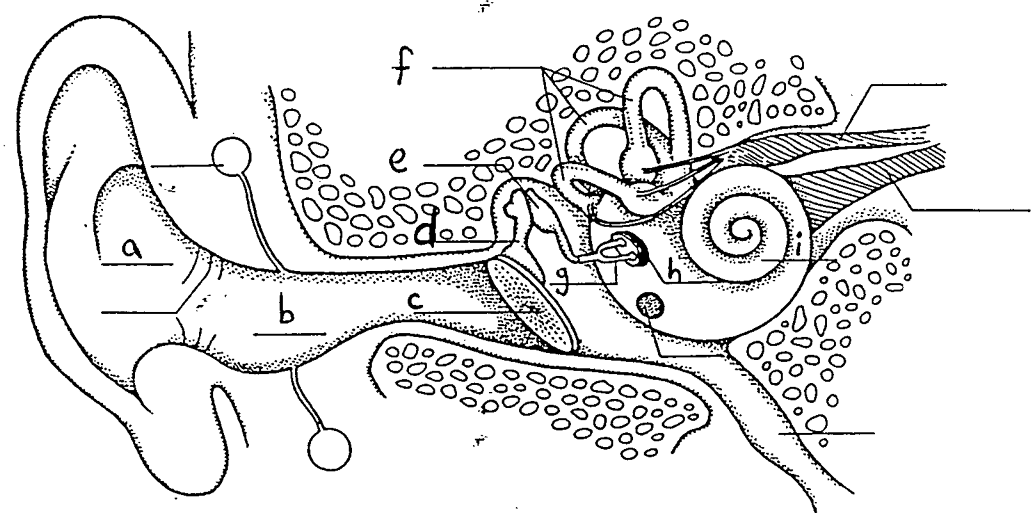
The Ear Quiz

Science 8
Mr. Webber

36
38

Full Name:
Block: A

1. Label the indicated parts of the ear in the spaces provided:



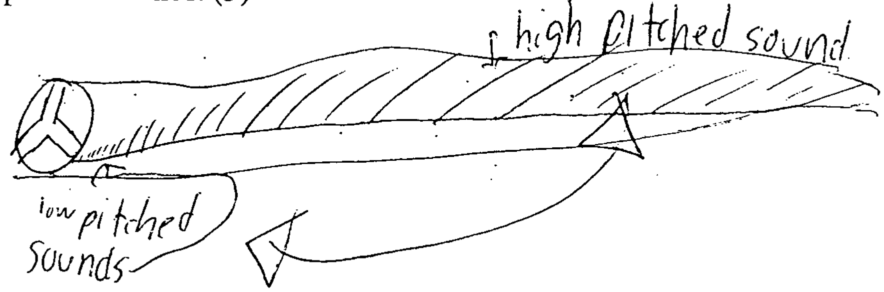
a. earflap ✓
b. earcanal ✓
c. eardrum ✓
d. hamer ✓
e. anvil ✓

f. ~~semie~~ semi circular canal ✓
g. stirup ✓
h. oval window ✓
i. cochlea ✓
j. auditory nerve ✓

2. The part of the ear that is filled with fluid is the cochlea ✓.
3. The part of the ear that **collects** the sound is called the earflap ✓.
4. The **semi-circular canals** help control our sense of balance ✓.
5. The thin membrane that vibrates when hit by sounds is the eardrum ✓.
6. What is the name of the nerve that connects the ear to the brain? auditory nerve ✓
7. The sense that never sleeps is the sense of hearing ✓.
8. What is **the** major cause of hearing damage? loud noise leveling our nerve endings in the cochlea ✓
9. In which **section** of the ear are the hammer, anvil, and stirrup? middle ear ✓
10. What determines your audible range? Why is a human's audible range different from other animals? (3)

What determins ~~ar~~ our audible range is the size of hairs in the cochlea.

11. Sketch an **uncoiled cochlea** showing the relative **lengths** of the tiny hairs. Indicate which hairs detect low-pitched sounds, moderate-pitched sounds and high-pitched sounds. (3)



12. You're playing basketball in the gym when the whistle blows to stop the game. Describe what happens to the sound of the whistle from the time it arrives at your outer ear until its information reaches the brain. (5)

~~a~~ The earflap scopes the sound makes your ear ~~d~~ drum vibrat ~~it~~ it then goes through the occicals to the semicircular canal where it maintaines it's balance trough the cochlea to determine the pitch and then through the auditory nerve to the brain. (all done in a ma of seconds)

13. Provide **two** different major causes of deafness or hearing loss. For each one describe the parts of the ear it damages, the hearing loss it creates and what can be done to correct the problem. (3 marks each)

a. ~~pop clogness of the ear can~~ puncturing the ear drum and it damages the ear drum. It usually repairs itself

b. loud noise levels the nerve endings it the ~~cochel~~ cochlea it is unfixable.

14. What causes your ears to *pop* when you change altitude? (2) (i.e. when you go up or down in a plane, car or bungee cord)

Your eardrum bends inward when you go low down and outward ~~w~~ when you go upward.

15. What is a major advantage of your eardrum being more than 25 times bigger than the oval window of the cochlea? (1)

It has to pick up more sound.

Bonus: *These answers have to be terrific to get any bonus points (1 per question).*

A. Explain how throat infections can create problems for your hearing.

The creep up the eustation tube and can severly damage the occicals

B. Explain why your voice sounds different when you talk to a friend compared to when you hear your voiced played back on an audiotape.

the sound is heard through your skull but when you talk it is heard head on.

Sound and Hearing Summary Questions

Science 8
Mr. Webber

Name: ________________
Block: ___

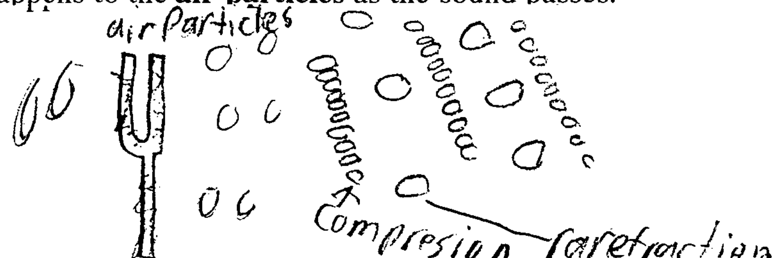
Sound

1. Explain how **pitch** and **frequency** are related. (2)

The higher the pitch the higher the frequency.

The lower the pitch the lower the frequency.

2. a. Sketch a vibrating tuning fork and indicate what happens to the air around it (i.e. compressions and rarefactions). Show the direction of the **sound**. Show what happens to the **air particles** as the sound passes.



3. a. Compare and contrast the **conduction of heat** with the **transmission of sound**.

Both are fastest in solids because solid's partilces are locked together.

b. You're on the **moon**. An asteroid strikes the other side of the moon. Would you hear the impact? Defend your answer.

No. Because the are no air particles for the sound to travel from.

4. a. What does the term **ultrasonic sound** mean?

Sounds so high we can't hear them.

b. Give several practical uses for **ultrasonic sounds**.

Pregnant woman chekcers, dog whistles, kidney stone crushers

5. Explain how **sound can reach you** even when **you cannot see** the source of the sound.

Sound can travel long distances but it can also bend around corners or ping pong off things.

6. Explain why when you search the sky for a plane it will appear to be **ahead** of the sound it makes.

Because it breaks the sound barrier in other words it goes faster than the speed of sound.

7. What sound frequencies can you hear? (i.e. the range and/or the numbers)

20 - 20 000 Hz

8. You are standing in front of a deep pot of water. You bang two rocks together vigorously underwater with your hands. Would you hear the sound of the rocks colliding? Explain. Assume your ears are functioning properly.

Yes because sound can travel through water particles.

9. How are **echoes** produced and are they always quieter than the original source of the sound?

It's sound waves bouncing of a solid source etc. (mountains) and it's quieter because the object absorbs some of the energy and it's also more spread out.

10. You're now a member of Jethro Tull. How can you produce a **higher pitched** sound on your **flute**?

You can blow harder or cover different holes.

11. a. What was the purpose of the pendulum experiment we did at the start of this chapter? (i.e. What connection did it have to objects that produce sound?)

to see if the lengh of somthing affects it's sound waves.

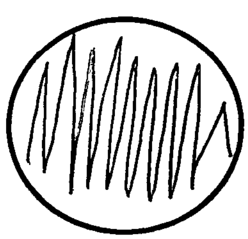
b. How did the **length** of the pendulum affect its **frequency**?

By making the pendulum more spread out so the sound travels farther.

12. Briefly explain what **sonar** is and what it can be used for.

Sonar is sending out a sound wave and seeing how long it takes to get back. It can be used to find were sunken boats are or treasures.

13. Sketch how a **loud, low frequency** sound wave would appear on an oscilloscope.



14. How are **sonic booms** produced?

By moving faster than the speed of sound you build up a wave that explodes. (SONIC BOOMS!)

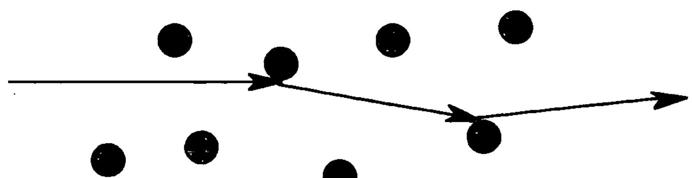
15. Do **sound particles** exist? What evidence supports your point of view?

No. Because it travels through other particles and sound cannot pass through a vaccumm.

16. Strayhorn came up with a theory about the transmission of sound. It says that sound should travel fastest through gases. This is because there are big enough spaces between the particles to allow sounds to pass through. Also, according to this theory sound travels next fastest through liquids. This is because even though the particles are close together there is enough space between them for the sound to rebound through. The particles act like little walls to rebound the sound through. According to this theory, sound cannot pass through a solid because the particles are *locked together* without any gaps to allow the sound to pass though. See the diagrams below illustrating this theory.

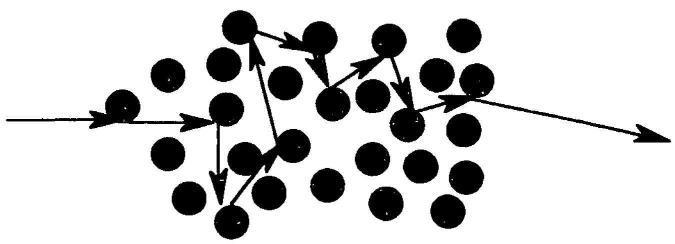
Sound Passing Through a Gas (Fastest)

Sound



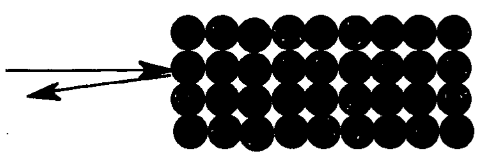
Sound Passing Through a Liquid (Next Fastest)

Sound



Sound Unable to Pass Through a Solid

Sound



Do the descriptions above match how the speed of sound changes in solids, liquids and gases? Explain.
(i.e. Which state of matter conducts sound the fastest and does this match the description?)

Sound travels fastest through solids. No.

17. In this classroom are many sinks with drain pipes that head straight down. As water from the faucet is directed down the drain it generates a sound. This sound changes pitch as the drain pipe fills with water. The pitch of the sound gets higher. **Explain this change in pitch.**

When filled lower pitch because the water muffels it and when empty higher

18. Design an experiment to calculate the speed of sound through air. Make a sketch if that helps you explain your answer.

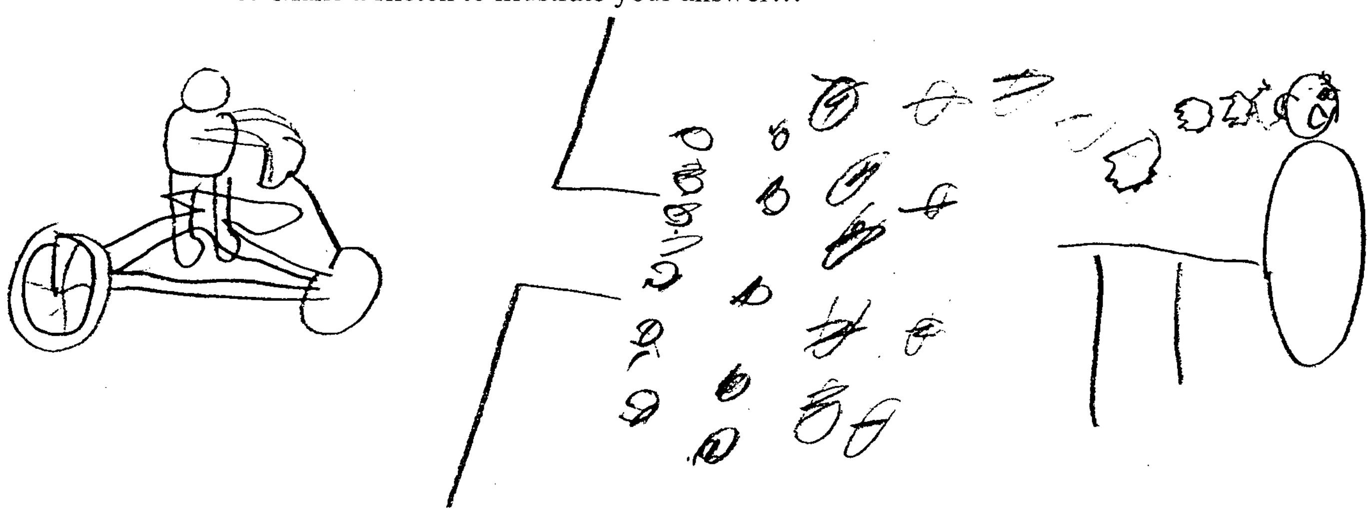
$S = D \div t$

I rest my case.

19. a. You are seated in a restaurant, far away from the front door. You hear a loud motorcycle (Harley Davidson) thunders by just as more customers open the front door. Are the particles of air carried from the door to you by the sound? Explain. (i.e. What happens to the particles as a sound passes by?)

The particles are vibrated so that's how they are carried.

b. Make a sketch to illustrate your answer!!!

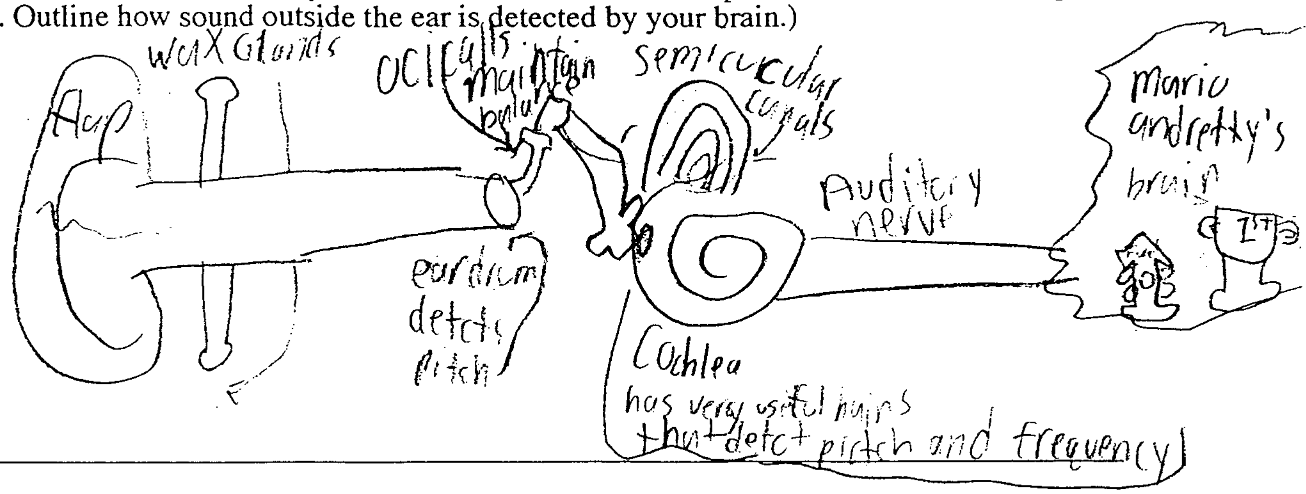


20. What are several reasons you cannot hear the sound of your eyes blinking?

It goes to fast.

The Ear and Hearing

1. Make a sketch of the ear as you understand it now. Then explain the function of each part. (i.e. Outline how sound outside the ear is detected by your brain.)



2. a. In detail, describe the structure and function(s) of the cochlea and explain how it works.
   It has nerve endings that detect pitch and frequency.

   b. The short hairs of the cochlea detect high - pitched sounds. (high or low)

3. a. The ear canal of your left ear becomes completely plugged with a large piece of bubble gum. Would you be completely deaf in your left ear? Explain.
   No, because some sound can slowly travel through the gum.

   b. Due to a soccer accident (running into a steel goalpost headfirst), the ossicles in your right ear separate from each other. Would you still be able to hear sounds with your right ear? Explain. No once there broken your deaf.

4. What are **two** different **major** causes of **hearing loss**?
Indicate what part(s) of the ear each affects and the type of hearing loss created. (i.e. is it air conduction, bone conduction, nerve conduction // temporary or permanent)

a. *Puncture eardrum temperary*

b. *loud noise leveling you nerve endings in the cochlea perment*

Final Comments

1. In terms of your life, why is it important for you to understand about the nature of sound? (This is a question about the relevance of learning about things around you -- and there are many *correct* answers.)

2. List anything related to sound that you already know about, that has not been dealt with by the questions above.

3. List anything related to sound that you would like to find out about, that has not been dealt with by the questions above or addressed during this unit on sound, hearing and the human ear.

4. What was the most interesting thing that you learned during this unit on sound and hearing?

APPENDIX 4

Preliminary Analysis of Bill's data

Introduction

Bill earned a high B in the first term and a C+ in the second. His test scores (80%) were similar to his scores on homework and labs and his first term mark was 82%. In the second term his overall mark was 68% and his test average was 67%. Bill was a cooperative student who had to work and study to learn new concepts. He tended to take time to learn new concepts, but once he had, his retention of ideas seemed strong. I selected him because I thought he would complete all the activities that are a part of this study. He had difficulties in writing, mainly spelling and grammar, but he tended to pack his answers with sufficient information to provide a context that made his answers understandable. Bill was not easily satisfied with his work.

TRANSMISSION

Transmission of Sound -- Collisions Data + States of Matter

On the preview question, Bill's conceptualization of sound transmission was that sound travelled like hitting a gong on one side of a room and a gong on the other side of the room vibrated. On clarification, he could not explain how the vibrations passed from one side of the room to the other, but he said that "somehow the gong making the sound caused the gong on the other side of the room to vibrate." He added that the sound of a bat hitting a ball "bounced off the bat and bounced around until it got to your ear." On his sketch of sound of the howling wolves travelling to the tent he drew wavy lines (that he labelled sound waves) and said that the sound waves rebounded off trees until they arrived at the tent. During probing, he said that sound travelled in waves that spread out from the source of the noise. On the preview question about whether sound could travel through all states of matter, Bill answered, "yes, because for all states you can hear sound." He added that you can hear sound "underwater, in a room and in the air." He said it was possible to hear underwater because sound passed through water. Contradicting his answer that sound could pass through all states of matter, Bill did not think that sound could pass through a solid wall because the sound waves would only bounce off the solid wall and produce an echo. He said that sound could not pass through a vacuum because it had nothing off which to bounce. He thought that sound travelled at the same speed all the time and was unable to change speeds.

On the sound test, Bill said that sound travelled fastest through solids. He said that heat conduction was similar to sound transmission because both occurred in all states of matter and both passed fastest through solids because the particles are locked together in solids. He said there was nothing wrong with the scene in which a spaceship was hit by a missile and the sound of the explosion was heard shortly after, because light travelled faster than sound. He said that it was possible to hear sounds underwater because sound did not travel in the form of sound particles and it could go through a liquid. Bill faced a counter-intuitive explanation for the different speeds of sound in solids, liquids and gases. The explanation argued that sounds should pass through gases the fastest and solids the slowest which is the reverse of what is observed in nature. Bill said that the description did explain how the speed of sound changes in solids, liquids and gases. He said "sound travels fastest in solids so it all matches up." In describing himself as an air particle in a room with a sound passing through, Bill said, "I would start to vibrate, bump into another student and she would vibrate and bump into another student and so on." On the test, Bill was asked to sketch, label and describe how the sound of a loud car reached him in a classroom when the window was open, and then when the window was closed. For the car's sound entering a classroom through an open window, he drew circles that increased in size, labelled them sound waves and said that they come from the car. These waves passed through the open window and spread out in the classroom. He said the sound the sound of the engine would pass through an open window to his ear. He also drew circular lines (representing sound waves) rebounding off the wall next to the window. For the situation with the closed window, he sketched particles vibrating within the wall, and drew smaller waves (to represent quieter sounds) passing to the person. He said most of the sound would bounce off the wall, "but some of it would seep through and to your ear." Bill's evidence that sound did not travel in the form of sound particles was based on the vacuum pump demonstration in which a balloon was burst in a bell jar under vacuum conditions and produced virtually no audible sound. He said, "we could not hear the balloon nearly as well as when it was outside the vacuum."

On the final questions, in comparing the conduction of heat and sound transmission, he said both heat conduction and sound transmission are fastest in solids because solids' particles are locked together. On clarification, he said that in a solid the particles are close together, so if one particle moves it will collide sooner with a neighbouring particle than it would in a gas. He said that no sound would be heard when the asteroid hit the moon because there were no air particles for the sound to travel through. He said that the rocks would make a sound when banged underwater "because sound can travel through water particles." Bill said that if your ear became plugged with gum, "you would not be completely deaf because the sound could slowly travel through the gum." Bill faced a counter-intuitive theory about the transmission of sound accompanied by three diagrams showing how sound would travel through a solid, a liquid and a gas. The theory was similar to the theory that appeared on the sound test, but was accompanied by three diagrams to illustrate the theory. The theory argued that sound should travel fastest through gases because there were big enough gaps between the particles did not have gaps between them to allow sound to pass through. Bill said the theory was incorrect because sound travelled fastest through solids. He said "sound needs particles, not gaps so the theory is completely backwards." He argued that sound particles did not exist because sound could travel through the three states of matter by particles colliding with their neighbours. He added that sound could not pass through a vacuum, and said that if sound particles existed they should be able to travel through empty space. In his picture of sound transmission from a tuning fork Bill drew dots representing air particles. He called the dots that were close together compressions, and the dots that were far apart rarefactions. The compressions and rarefactions were to the right of the tuning fork, but he did not indicate the direction of the sound. For the diagram of the motorcycle's noise entering the restaurant, he sketched a motorcycle and the particles [air] in the restaurant. He provided few details for how the sound travelled, stating that the particles vibrated and collided with their neighbours to carry the sound. He did not draw sound waves and did not include waves in his description of how the sound passed into the restaurant.

Transmission of Sound Collisions -- Discussion

Confused conceptualization

On the preview questions, Bill had a confused conceptualization of sound transmission. He knew that sounds were produced by objects that vibrated, and sound travelled in the form of waves. He could not explain how the wave travelled, and because he did not realize that particles were required for sound transmission, he could not describe the effect of the sound wave on the particles as the sound passed. He thought that sound could travel only in straight lines without bending. His explanation for how sound travelled was unclear. When asked to select from five conceptions of how sound travels, Bill provided his own conceptualization, stating that sound travelled "like hitting a gong from one side of the room and the other one [gong] vibrates [on the other side of the room]." During probing he said he did not know what happened between the two gongs, but the first one made the second gong vibrate. For the diagram of the sound of the wolves howling, the main feature was his sketch of sound waves rebounding off trees until they reached the camper in the tent. On the preview questions, the elements of Bill's conceptualization of sound transmission that fit the scientific perspective were that sources of sound vibrated, sound travelled in the form of waves and could rebound off objects. He was unable to describe and explain sound transmission at the microscopic level of particle collisions and compressional waves.

Scientific conceptualization

On the sound test, Bill had developed a scientific conceptualization of sound transmission, but lacked detail in some aspects of his description. While he retained his earlier conceptualizations that sources of sound vibrated and sound travelled in the form of waves, on the test he was able to explain that a sound source created compressional waves that caused particles to collide in a series of chain reactions. In his response to the question of what would happen to his classmates and him if they were air particles in a classroom as a sound passed through, he described the chain reaction. He said he would vibrate, bump into another student, who in turn would bump into another student. He said that sound transmission was similar to the conduction of heat and he knew that while the sound passed outwards from the source, the particles did not travel with the sound, but remained in the same general area. Bill argued correctly against the idea of sound particles, special particles that carried sound. He based his argument on the vacuum pump demonstration and said that if sound particles existed, they should have been able to pass through a vacuum. He did not link his argument against sound particles to his previous discussion of a chain reaction of particle collisions. In Bill's conceptualization of sound transmission there remained some areas that lacked detail. Although he said that sound travelled in the form of a compressional wave, he did not mention compressions and rarefactions in his diagrams of sound transmission, let alone describe how the compressions and rarefactions were produced. Overall, on the test, Bill was able to provide greater detail about the microscopic events involved in sound transmission than he had on the preview questions. His conceptualization fit the scientific perspective.

<u>Confused conceptualization</u>

On the final questions, Bill's conceptualization of sound transmission was confused. At one point on the final questions he correctly stated that that sources of sound vibrated and created a compressional wave. He also stated that sound transmission was similar to heat conduction. At another point he said that sound transmission was "like light because sound can bounce off stuff." In his diagram of sound travelling from a tuning fork, he included alternating regions labelled compressions and rarefactions. He continued to argue against sound particles on the basis of his observation that sound could not pass through a vacuum. He said that if sound particles existed, sound should have been able to pass through a vacuum. His description of how sound travelled was limited to the "particles are vibrated," but he knew that the particles did not travel with the sound waves.

Over the course of this study, Bill shifted from a confused conceptualization (on the preview questions) to a scientific conceptualization (on the sound test) and finally to a confused conceptualization of sound transmission (on the final questions). At the beginning of the study he thought that sound travelled in the form of waves and echoed off objects. Over the period of the units on sound and hearting, the major developments in Bill's conceptualization of sound transmission were his awareness that sound required particles to pass through and his comparison of sound transmission to heat conduction based on particle collisions. Of all the different stages of the study, his description of how sound travelled was the most detailed and accurate on the sound test, but he retained much of the information on the final questions. Throughout the study, his major difficulty was in explaining how sound waves and particle collisions were related.

States of Matter -- Discussion

Confused conceptualization

On the preview questions, Bill appeared to have a confused conceptualization of how sound passed through the states of matter. Bill's prior ideas about sound transmission shaped his conceptualizations of how sound passed through solids, liquids and gases. On the preview questions, Bill's conceptualization of sound transmission was that sound waves rebounded off objects. He did not know that sound transmission required particles and that the different arrangements of particles in solids, liquids and gases influenced the speed of sound through each state. Initially, Bill stated correctly that sound could pass through solids, liquids and gases. On another question he contradicted himself when he said that sound could not pass through a solid because the sound would just bounce off. He thought incorrectly that sound could travel at only one speed and not change speeds. Although he correctly said that sound could not pass through a vacuum, his reason was that there was nothing for the sound to bounce off, rather than stating that a vacuum lacked particles to transfer the sound through. In sum, Bill's conceptualization of sound transmission matched the macroscopic properties of sound, but he was unaware of how sound transmission occurred at the microscopic level of particles.

Scientific conceptualization

On the sound test, Bill had a scientific conceptualization of how the states of matter affected sound transmission. He was able to describe the role of particles in sound transmission. Corresponding to this development in his conceptualization of sound transmission, Bill explained how the arrangement of the particles in solids, liquids, and gases affected the speed of sound through each state of matter. Unlike his response on the preview questions, on the test Bill not only knew that sound could pass through a solid, but was also able to explain how. He knew that sound passed fastest through solids and slowest through gases. He explained that sound was fastest in solids because the particles were close together and the chain reaction of collisions between particles occurred rapidly. In his diagram of the car's sound passing into the classroom, Bill drew sound waves bouncing off the wall, but he also showed the particles of the wall vibrating and said that some of the sound would "seep through the wall." Bill said that sound could not pass through a vacuum, because there were no particles to vibrate. There was an inconsistency in Bill's conceptualization of sound transmission through the states of matter. Bill faced a counter-intuitive theory for the different speeds of sound in solids, liquids and gases that argued that sounds should pass through gases the fastest and solids the slowest which is the reverse of what is observed in nature. Bill said that the description made sense and correctly explained how the speed of sound changed in solids, liquids and gases. His response was surprising because his earlier responses that explained why sound travelled fastest through solids appeared coherent and strongly rooted, and while he still believed that sound travelled fastest through solids, the theory argued that sound should travel fastest through gases. For the situation of seeing a spaceship explode shortly before the sound was heard, Bill thought the question was referring to the relative speeds of sound and light. He was unaware that the intent of the question was to probe whether he recalled that sound could not through a vacuum (in this case outer space).

Scientific conceptualization

On the final questions, Bill had a scientific conceptualization of sound transmission through the states of matter. He said that sound could travel through solids, liquids and gases, but not through a vacuum. He argued that no sound would be heard on the moon because the moon had no particles (no atmosphere) for the sound to pass through. He answered correctly that the sound of two rocks banging underwater could be heard because the vibrations could pass through the water particles and then through the air above. Bill countered the theory that sound should pass through gases the fastest because gases have the largest gaps between particles. He said the theory was wrong because he recalled that sound passed fastest through solids. He added that "sound needs particles not gaps, so the theory is completely backwards." He added that because the particles are *locked together*, the particles collide fastest in solids. The only identified area of confusion in Bill's conceptualization of sound transmission through the states of matter occurred when he answered the question about whether or not he would become completely deaf in an ear that was plugged with gum. Although Bill knew that sound should pass through solids the fastest and explained why, he had difficulty in applying this information to the situation of hearing. He correctly answered that he would not become completely deaf in that ear, but he said that the sound "can slowly travel through the gum." The sound would have passed from air (a gas) through the gum (a solid) so the sound should have sped up, not slowed down, according to what he had stated earlier about the speed of sound in each state of matter. He realized the solid would reduce the loudness of the sound, but he also associated the decrease in loudness with a decrease in the speed of the sound.

The one area of concern about Bill's conceptualization of sound transmission through the states of matter was how sound passed through solids. Although on the test and final questions he answered that not only could sound pass through a solid, but travelled fastest through a solid, he seemed to have difficulty believing this property of sound. His answers appeared to be influenced by his initial conceptualization that sound bounced off solids and did not pass through them. His macroscopic observation that sounds were quieter after passing through a solid indicated to him that it was harder for sound to pass through a solid and therefore sound was slowed down or stopped by a solid.

During the investigation, Bill shifted from a confused conceptualization on the preview questions to a scientific conceptualization of how sound passed through the different states of matter on both the sound test and on the final questions. Throughout the study he knew that sound could pass through all states of matter, but not through a vacuum. On the preview questions he could not explain how sound transmission occurred through solids, liquids and gases, but on the sound test and final questions he described the relationship between how sound travelled and the states of matter. Apart from his difficulties believing that sound could pass through solids, Bill appeared to have a scientific conceptualization of how sound passed through the states of matter.

Sound vs Light -- Data

On the preview questions, Bill said that light travelled faster than sound "because it could take a while for sound to reach your ear from a distance but light can get to your eyes from a distance." On clarification, he said that "light can travel farther than sound because light comes from stars that are a long distance away, but sounds cannot go that far."

On the sound test he said that sound travelled at 340 m/s. He explained that we see lightning before we hear the thunder, because "light moves way faster at 300 000 km/s than sound at 340 m/s."

On the final questions, his explanation for why an airplane appeared to be ahead of the sound it made was that the airplane breaks the sound barrier. On clarification, he explained that the airplane goes faster than the speed of sound creating sonic booms. He said he knew this from going to the Abbotsford Air Show and hearing the sonic booms the airplanes created.

When I asked him whether all airplanes appeared to be ahead of the sound they made, he said, "no, only those that go faster than the speed of sound." Bill did not design an experiment to determine the speed of sound. Instead he listed an algebraic formula that related speed, distance and time. On clarification, he said he knew how to calculate the speed of sound, but sound went too fast to measure.

Sound vs Light -- Discussion

Scientific conceptualization (limited data)

On the preview questions, Bill seemed to have a scientific conceptualization of the relative speeds of sound and light, but there was insufficient data to make a strong case. Fitting the scientific perspective, he knew that light travelled faster than sound. He also thought that light could travel farther than sound and based this on his observation that he could see stars that were great distances from the earth.

Scientific conceptualization

On the test, Bill had a scientific conceptualization of the relative speeds of sound and light. Not only did he know that light travelled faster than sound, he correctly listed the respective speeds. He applied the information about the speeds of sound and light to explain why lightning was seen before the accompanying thunder was heard.

Difficult to classify his conceptualization

On the final questions, it was difficult to categorize Bill's conceptualization about the relative speeds of sound and light. For the question of why an airplane appeared to be ahead of the sound it made, he focused on the relative speeds of sound and the airplane rather than the relative speeds of sound and light. Although his answer was not wrong, he did not explicitly state that light travelled faster than sound. It was only when questioned directly about the relative speeds of sound and light that Bill stated that light travelled faster than sound. He said that sound took time to cover a distance and during that time the plane was moving forward. He thought that the airplane was travelling faster than the speed of sound so the airplane was ahead of the sound.

It was difficult to categorize Bill's conceptualizations of the relative speeds of sound and light on the preview questions and the final questions. Throughout the study, he knew that light travelled faster than sound, but it was only on the test that he listed their respective speeds. What his answers revealed was that he was careful in his interpretations of observations. For example, based on his observations that he could see light from distant stars, but not hear sounds from that far away, he concluded that light travels farther than sound. Similarly, his experiences at the Abbotsford Air Show watching supersonic airplanes seemed to play a major role in his response that it was the relative speeds of the airplane and sound that caused the sound to seem to be behind the airplane. While his answers did not provide a direct comparison of the speeds of sound and light, his responses fit his observations and demonstrated that he was skilled at interpreting data.

Waves -- Data

On the preview questions, Bill used the term "sound waves" several times. In one instance he said that sound could not travel through a solid wall because the sound waves bounced off the wall. He also used the term sound waves in his diagram showing how the sound of howling wolves rebounded off trees as it travelled through the air to the camper in the tent. When I asked him what a sound wave was, he said he wasn't sure, but he thought it might be something like a water wave.

On the sound test, Bill correctly answered that in rarefactions the air particles were spread out. He said the ripple tank demonstration provided evidence that sound travelled in the form of waves. Bill said he knew that sound travelled as a compressional wave because he could see the compressions when the slinky was wiggled. For a sketch of how a quiet, high frequency sound wave would appear on the oscilloscope he correctly sketched the peaks close together, but incorrectly drew peaks and troughs with large amplitude. In identifying an oscilloscope's wave representations of sound he correctly selected the waves representing the quietest sound and noise, but incorrectly selected the wave representing the quietest sound instead of the lowest pitched sound. He said that an oscilloscope gave a misleading representation of sound becauses it made sound look like a transverse wave instead of a compressional wave. He said a firecracker sounded much louder when it was set off 1 metre away than 1 kilometre away because sound travels in metres per second, not kilometres per second. On clarification, he said sound would have more time to lose energy if it travelled 1 kilometre. In describing what would happen to him if he were an air particle and a sound was passing through, he said he would start to vibrate and bump into a classmate and make her vibrate and she would bump into another classmate and make him vibrate and so on. When I asked him if he would travel with the sound he said that "he probably wouldn't." In his diagram of the car engine's sound reaching him in a classroom, he sketched circles representing sound waves that increased in size around the car.

On the final questions, Bill sketched a tuning fork showing air particles that were close together and labelled them compressions. Next to the compressions he drew air particles that were farther apart and labelled them rarefactions. He did not indicate the direction of the sound or the particles. His sketch of a loud, low frequency sound's appearance on the oscilloscope corresponded to a loud high frequency sound, meaning the peaks were high and close together. He said a sonic boom was produced "when you moved faster than the speed of sound and built up a wave that exploded."

Waves -- Discussion

Confused conceptualization

Bill had a confused conceptualization of sound waves on the preview questions. He had heard of the term sound waves and included them in his diagram of the sound of the howling wolves travelling to the tent. Although he said that sound travelled as a wave and could rebound off objects, he did not provide more details. He did not state that sound travelled as a compressional wave creating a series of compressions and rarefactions, or that sound waves could bend around objects, or that sound spread out in all directions from a source.

Confused conceptualization regarding oscilloscope and quietness

On the sound test, Bill had a confused conceptualization of sound waves. He said that sound travelled as a compressional wave and created compressions and rarefactions. He said that sound waves could travel around a corner by echoing off walls or bending. The ripple tank demonstration reinforced his idea that sound travelled as a wave. He cited the demonstration in his argument that sound travelled as a wave. His diagram of the sound waves leaving the car engine was similar to the diagrams in his notebook of the waves bending around corners, rebounding off objects, and spreading out from a source in the ripple tank demonstration. He did not mention sound waves spreading out to explain why a firecracker was much louder if it is set off 1 metre away that 1 kilometre away. Although he said the slinky demonstration showed that sound travelled as a compressional wave, he could not explain how. Bill said that the oscilloscope made sound look like a transverse wave rather than a compressional wave, but he did not distinguish between the two wave forms. He confused how the oscilloscope represented pitch and loudness when he selected the wave representation of the quietest sound rather than the lowest pitched sound. In attempting to sketch how a quiet, high frequency sound appears on an oscilloscope, he drew a low, high frequency sound. He had difficulty distinguishing between how an oscillscope represented loudness and pitch. From the start of the study, Bill thought that sound travelled in the form of waves. He claimed that the demonstrations (ripple tank, slinky, and oscilloscope) *proved* that sound travelled in the form of waves.

Confused conceptualization regarding oscilloscope and quietness

On the final questions, Bill had a confused conceptualization of sound waves. Although he retained his idea that sound travelled as a wave, his description of sound waves was limited to a sketch of compressions and rarefactions. In his diagram of sound travelling from the motorcycle into the restaurant he did not include waves, and did not show the sound spreading out in all directions. He recalled that sounds could be heard even when the source was out of sight because waves could bend around objects or "ping pong" off walls to travel around corners. He also remembered that a sound got quieter as the energy spread out. In sketching how a loud, low frequency sound would appear on an oscilloscope, the wave he drew represented a loud, high frequency sound. He continued to have difficulty distinguishing between pitch and loudness.

Over the course of this study, Bill shifted from a confused conceptualization on the preview questions to a confused conceptualization of sound waves on the sound test and final questions. Throughout the study, Bill said that sound travelled in the form of waves. On the preview questions, he did not know how waves travelled. On the test and final questions he said that sound travelled as a compressional wave and there were regions called compressions and rarefactions. The major difficulties in his conceptualization of sound waves was that he could not explain how a sound wave, particle motion, and compressions and rarefactions were related. He had difficulty representing sound waves on an oscilloscope. Although he said the demonstrations were convincing, the intended outcome of each demonstration did not transfer to him. He did not understand that the slinky demonstration provided a representation of two wave forms (compressional and transverse) and the coils of the slinky represented particles. He had difficulty remembering how an oscilloscope represented the loudness and pitch of a sound. The general problem appeared to be that Bill did not recognize that the demonstrations were limitied in how closely they represented sound waves. The strengths of Bill's conceptualization of sound waves seemed to be based on his observations during the ripple tank demonstration. He was able to transfer the behaviour of water waves to the behaviour of sound waves. He remembered that waves spread out in all directions, and bent around and rebounded off objects. The ripple tank, played a major role in shaping his conceptualization of sound waves on the test and final questions.

Echoes -- Data

On the preview questions, Bill said that sound could travel only in straight lines, but not around corners. Then he said that sound could bounce off something. On clarification he said that "sounds cannot bend around corners and the only way sound could get around a corner was if it [they] bounced off something." He said that echoes were sounds made when sound bounced off something like a mountain and back to your ear. He provided no reason for why echoes were quieter than the original sound.

On the sound test, he said that one way for sound to go around corners was to "pinball off the walls" and the other way was it could bend around corners. On clarification, he said that the term "pinball" meant bounce, so the sound could bounce off the walls to get around the corner. He added that the ripple tank demonstration had showed waves bending around corners, and since sound was a wave, sound could bend as well. On the sound test, Bill said that "the echo occurs by your sound waves rebounding off the rock walls and back to your ears." He explained that the echo was quieter "because the wall absorbs some of the energy and because the energy is more spread out." He said that echolocation is "when something makes a noise and you see how long it takes to travel back to it." He added that we use echolocation for "stuff like sonar."

On the final questions he said that even when you cannot see the source of the sound, "sound can travel long distances and bend around corners or ping pongs off things" to reach you. He said that echoes are sound waves bouncing off solids and echoes are quieter because the object absorbed some of the energy and the sound is more spread out. He said sonar involved sending out a sound wave and seeing how long it took to get back. He added that sonar could be used to find where boats or treasure were.

Echoes -- Discussion

Confused conceptualization

On the preview questions, Bill's conceptualization of how echoes occurred fit the scientific perspective. He knew sound could travel around corners by bouncing off other walls. Echoes were a significant component of his description of sound transmission. Bill's conceptualization of echoes could not account for why an echo was quieter than the original sound. At this stage he did not have a clear conceptualization of sound transmission and could not describe the details of what happened when a sound rebounded off an object. Thus it was not logical to categorize his conceptualization of echoes as fitting a scientific perspective.

Scientific conceptualization

On the sound test, Bill had a scientific conceptualization of echoes. He was able to explain how they occurred and apply his ideas to explain how sound could travel around corners and be used in echolocation. The major addition to his conceptualization of echoes was his ability to explain why an echo was quieter than the original sound. Based on the ripple tank demonstration he recalled that the waves had spread out by the time they returned to the source. He said that the energy had spread out. He also said that some of the sound's energy was absorbed by the wall indicating that he recalled our discussion of energy transformations several units prior to our investigation of sound. Bill described the process of echolocation, emphasizing that the total time of the sound's round trip was used to calculate how far away an object was. He knew that sonar was an example of echolocation. Overall, on the test Bill's conceptualization was consistent with the scientific perspective.

Scientific conceptualization

On the final questions, Bill continued to have a scientific conceptualization of echoes. His answers were similar to those on the sound test and he was able to explain how echoes occurred, what echolocation was used for and how it worked, and he provided two reasons for why an echo was quieter than the original sound. His description of sonar was detailed as he outlined what sonar involved and was used for.

As the study progressed, Bill shifted from a confused conceptualization on the preview questions to a scientific conceptualization of echoes on both the sound test and the final questions. Throughout the investigation, he knew that echoes were rebounded sounds, but it was on the test and final questions that he could explain how an echo occurred and provide two correct reasons for why an echo was quieter than the original sound. The ripple tank demonstration played a major role in his conceptualization of how echoes occurred and how they became quieter. On both the test and final questions he drew detailed diagrams illustrating how sound waves hit a wall and reflected back. The diagrams were similar to those in his notebook based on the ripple tank demonstration. The demonstration also provided a mechanism for him to remember how echoes occurred. On the final questions his conceptualization of echoes was virtually identical to his conceptualization on the test. In direct terms he answered the questions indicating that he was confident with the topic of echoes. He did not have to mask his responses with sound terminology to give the impression that he knew what he was talking about.

FREQUENCY

Frequency / Vibrations -- Factors Affecting it -- Data

Initially, Bill thought that all sources of sound travelled in waves and vibrated in peoples' ears or whatever they hit. He described the sound in the stadium as people's vocal cords and the echo off the walls of the stadium. He did not describe the sound produced by a mosquito. Bill said the pitch told us the deepness of the sound. In order to produce a higher pitched sound he said "the setting on the amplifier could be changed." For the change in pitch as an ambulance approached he said the sound went from low to high and depended on how close the ambulance was. On clarification, he said that he meant the sound got louder as the ambulance neared.

On the multiple choice section of the sound test, Bill correctly answered that all sources of sound vibrated, that long pipes made lower notes, and that frequency was measured in hertz. He correctly identified the definitions of the terms frequency of vibration and natural frequency. On the short answer section of the test, Bill explained that the higher the frequency the higher the pitch and the lower the frequency the lower the pitch. For making a higher pitched sound with a guitar, he suggested that "you chould pluck the strings harder or shorten the strings with your fingers." For changing the pitch of a drum he suggested hitting the drums harder. He defined vibration as something moving back and forth. He said the purpose of the experiment was to see if the length of something affected its sound, and he said "when you lengthen it [the pendulum] it [the sound] becomes louder."

On the final questions, he described the relationship betwen pitch and frequency as the higher the frequency the higher the pitch, and the lower the frequency the lower the pitch. He explained that to increase the pitch of a note on the flute "you could blow harder or cover different holes." For the purpose of the frequency lab he said "we did the experiment to see if the length of the pendulum affected its sound waves." He added that by making the pendulum longer, the sound travelled farther. For the water filling the drain pipe, Bill said that when the pipe filled the sound was a lower pitch because the water muffled it (the sound), and when empty it was a higher pitch because the sound was not muffled.

Frequency / Vibrations -- Factors Affecting it -- Discussion

Confused conceptualization

On the preview questions, Bill had a confused conceptualization of frequency. In describing the sounds of a mosquito and the crowd in a stadium, he did not mention the terms loudness and pitch. Instead he mentioned that the sounds would echo. On other questions, he thought that the pitch of a sound described the sound's loudness. His confusion between pitch and loudness was demonstrated when he said an amplifier could be used to increase the pitch of a sound, and when he said the pitch of an ambulance's siren got higher as the ambulance approached and the sound got louder. He also said that pitch described the "deepness of a sound", but during clarification he had difficulty explaining what the term deepness meant. He decided to define deepness as meaning loudness (i.e. a louder sound was deeper than a quiet sound), but he did not seem satisfied with this definition.

Confused conceptualization

On the sound test, Bill had a confused conceptualization of frequency. At times it appeared that he understood the concept of frequency. He correctly defined frequency and vibration and knew that as the frequency of a sound source increased, the pitch of the sound also increased. He knew that long pipes on an organ made lower notes. He correctly described the purpose of the frequency lab was to investigate how the length of the pendulum affected the sound, but at this point inconsistencies in his conceptualization became apparent. He thought that the length of the pendulum affected oudness rather than frequency. This was an interesting conclusion, because the pendulum should not have produced an audible sound, and the lab was entitled "Frequency Lab." While he correctly stated that a higher pitched sound could be produced on a guitar by using a shorter string, he added incorrectly that plucking the strings harder would also increase the pitch. Plucking the strings harder should increase the loudness of the sound, not the pitch. Similarly, he said hitting the drums harder would increase the pitch of the sound, rather than the loudness of the sound. While Bill could remember definitions of terms such as frequency and pitch, and how the length of an object (or musical instrument) affected the pitch of the sound it produced, he did not apply this information successfully to other questions. Bill's major problem with his conceptualization of frequency was that he had not properly distinguished between the loudness and pitch of a sound. He used the terms interchangeably.

Confused conceptualization

On the final questions, Bill had a confused conceptualization of frequency. He knew that pitch and frequency were related terms and correctly explained that as the frequency increased the pitch increased, and as the frequency decreased the pitch decreased. He stated that the purpose of the frequency experiment was to see how the length of the pendulum affected the sound waves. On the test he had stated that as the length of the pendulum increased, the loudness increased, but on the final questions he said that as the length of the pendulum increased, the sound travelled farther. His conceptualization was that a longer string produced a *stronger* sound that could travel farther. In his response to the question that described the pitch increasing as water filled a drainpipe, Bill did not mention the change in pitch. Instead, he described changes in the loudness of the sound and related the lower pitched sound at the beginning to a "muffled" or quieter sound. Similarly, he linked the higher pitched sound to an "unmuffled" or louder sound. He associated low pitch with quiet sounds and high pitch with loud sounds. Again, Bill had not made a distinction between the pitch and loudness of a sound.

Over the course of the study, Bill shifted from a confused conceptualization on the preview questions to a confused conceptualization of frequency on both the sound test and the final questions. On the test and final questions he was able to provide definitions of terms related to frequency and pitch, but throughout the study he had difficulty distinguishing between the pitch and loudness of a sound. This problem was evident in his interpretation of how an oscilloscope represented the pitch and loudness of a sound. His use of the terms pitch and loudness interchangeably made it difficult for him to apply his conceptualization of frequency to situations that demanded more than memorizing definitions of terms.

Frequency Ranges -- Data

On the preview questions, Bill said that ultrasonic sounds were "sounds that moved so fast that we can't hear them." On clarification, he said ultrasonic sounds travelled too fast to be heard. He said that ultrasonic sounds could be "used to look at a baby in a mother's stomach" (i.e. the developing fetus in a pregnant woman). During probing, he said that he had not heard of the term infrasonic sound.

On the multiple choice section of the sound test, he correctly answered that: infrasonic sounds are too low to be heard by humans; a bat uses echolocation to fly and hunt in the dark; and that earthquake waves are an example of infrasonic sound. As examples of uses of ultrasonic sounds he listed, "pregnancy baby checkers [referring to checking the fetus of a pregnant woman], kidney stone crushers, and a dog whistle to call Fifi." As well as describing echolocation, he identified it as a use of ultrasonic sound in sonar. He said the frequencies he could hear were from 20 Hz to 20 000 Hz. For the sketch of an uncoiled cochlea, he drew tiny hairs of different lengths. He reversed what the tiny hairs detected, indicating that the long hairs detected high pitched sounds and the short ones detected low pitched sounds.

On the final questions, Bill said that ultrasonic meant "sounds so high we can't hear them." He said the sounds he could hear were from 20 Hz to 20 000 Hz. He said the cochlea had tiny hairs that detected pitch and frequency. He explained that the short hairs of the cochlea detected high-pitched sounds. He said that sonar involved sending out a sound wave and seeing how long it took to get back and could be used to find where sunken boats or treasure are. As examples of uses of ultrasonic sounds, he listed "pregnant woman checkers [again referring to checking the fetus of a pregnant woman], dog whistles and kidney stone crushers."

Frequency Ranges -- Discussion

Confused conceptualization

On the preview questions, Bill had a confused conceptualization of the frequency ranges. He had heard of ultrasonic sounds and gave a correct use of ultrasound, but he thought incorrectly that ultrasonic sounds were so named because they travelled faster than other sounds. He did not know that ultrasonic sounds vibrated too rapidly for humans to hear. He was not aware of the infrasonic sound range.

Scientific conceptualization

On the sound test, Bill had a scientific conceptualization of frequency ranges. He correctly identified a definition and an example of infrasonic sound. He listed correctly the frequencies that humans can typically hear. He gave three correct applications of ultrasonic sounds.

Scientific conceptualization

On the final questions, Bill had a scientific conceptualization of frequency ranges. His examples of uses of ultrasonic sounds were the same as those he listed on the sound test (ultrasound to examine a developing human fetus, dog whistle, and kidney stone crusher). He listed his audible range as 20 Hz to 20 000 Hz.

As the study progressed, Bill shifted from a confused conceptualization on the preview questions to a scientific conceptualization of the frequency ranges on both the sound test and the final questions. On the preview questions, Bill's conceptualizations of the frequency ranges was limited to knowing one use for ultrasound. He thought that ultrasonic sounds travelled faster than other sounds. On the test and final questions he gave detailed and coherent descriptions of the different frequency ranges and their uses, particularly echolocation. The topic of frequency ranges did not require abstract conceptualizations. The questions about frequency ranges required memory of facts (frequency numbers, examples and uses) for each frequency range and Bill did this successfully.

EAR

The Ear: Structures / How it Functions -- Data

On the preview questions, Bill's diagram of the ear consisted of sound waves arriving at the outer ear [ear flap] and passing to the eardrum which was connected to the brain. He said "the ear detected sound by vibrations in the eardrum." He said humans could not hear all sounds and used a dog whistle as an example of a sound that dogs could hear, but not humans.

Having completed the first unit on sound, but prior to the unit on the ear and hearing, Bill's ear design, consisted of an outer ear, a large canal leading to an eardrum and a tube that continued to the brain. His description of the function of the ear was that the eardrum vibrated to detect the loudness and pitch of a sound. He included a noise flap to eliminate unwanted sounds (of parents and teachers).

On the Ear Quiz Bill correctly labelled the indicated ear structures. On the fill in the blank section of the quiz, he said that: the part of the ear that is filled with fluid is the cochlea; the part of the ear that collects the sound is called the ear flap; the semi-circular canals help control our sense of balance; the thin membrane that vibrates when hit by sounds is the eardrum; the name of the nerve that connects the ear to the brain is the auditory nerve; the sense that never sleeps is the sense of hearing; and the section of the ear that consists of the hammer, anvil, and stirrup is the middle ear. Bill said the size of the hairs in the cochlea determined our audible range. For the sketch of the cochlea, he drew tiny hairs of different lengths. He reversed what the tiny hairs detected, showing that the long hairs detected high pitched sounds and the short hairs detected low pitched sounds. He described the path of the sound of the whistle as being scooped by the ear flap, the sound made the eardrum vibrate and went through the ossicles to the semicircular canal "where it maintains its balance." He said the sound then entered the cochlea to determine the pitch and then through the auditory nerve to the brain. He said the sound passed through the ear "in a matter of seconds." He said the main advantage of the eardrum being bigger than the cochlea's oval window was that it allowed the ear to pick up more sound.

On the final questions, in the proper sequence he drew the flap, wax glands, ear canal (unlabelled), eardrum, ossicles, cochlea, auditory nerve, and brain. He said the eardrum detected pitch, the ossicles maintained balance, and the cochlea detected pitch and frequency. He said the cochlea had tiny hairs that detect pitch and frequency and that the short hairs of the detected high-pitched sounds.

<u>The Ear: Structures / How it Functions -- Discussion</u>

<u>Confused conceptualization</u>

On the preview questions, Bill had a confused conceptualization of both the ear's structure and function. The structures he included in his ear diagram were an ear flap, eardrum and the brain. He had to guess what the ear consisted of. On the preview questions, Bill had a narrow conceptualization of sound. He thought that sound vibrated, travelled in waves and echoed off objects as it travelled. He did not discuss pitch, frequency, or loudness in his description of sound transmission. Similarly, his description of the function of the parts of the ear was narrow with no mention of how the loudness and pitch of a sound would be detected. His explanation of what happened to the sound from the time it arrived at the ear flap until it reached the brain was limited to stating that sound was detected by vibrations in the eardrum.

<u>Confused conceptualization</u>

On the *Ear Design* assignment, Bill had a confused conceptualization of both the ear's structure and function. In addition to the ear flap, eardrum and the brain that he included on the preview questions, his ear diagram contained tubes and a flap (to filter out unwanted sound). Bill had not seen a picture or model of the human ear so he was forced to guess what the ear consisted of. On the *Ear Design* assignment, Bill attempted to incorporate two properties of sound, pitch and loudness, that he had not dealt with on the preview questions. Instead of describing the eardrum's function as detecting vibrations, he said that the eardrum detected the pitch and loudness of a sound. He did not provide details of how the eardrum detected the pitch and loudness of a sound. Essentially, Bill tried to create an ear with limited knowledge of sound transmission and human anatomy.

Scientific conceptualization of structure confused conceptualization of function

On the Ear Quiz, Bill had a scientific conceptualization of the structure of an ear. He correctly labelled the indicated parts on a diagram of the ear. While his conceptualization of the functions of the parts of the ear generally matched the scientific perspective, there were several indicators of confusion. On the fill in the blank section of the quiz, he correctly listed the ear structure associated with each function. He correctly sketched how the hairs in an uncoiled cochlea would appear but reversed the respective pitches the hairs would detect. He incorrectly said that the short hairs would detect low pitched sounds, and the long hairs would detect high pitched sounds. In describing the path of sound through the ear, incorrectly stated that the sound would pass through the ossicles to the semicircular canals to maintain balance before reaching the cochlea. He had directly linked the sense of balance to the sense of hearing. Apart from that error, his description of sound passing through the ear fit the scientific perspective.

Scientific conceptualization of structure confused conceptualization of function

On the final questions he had a scientific conceptualization of the structure of an ear. His diagram of the ear was similar to the picture in his textbook. It was drawn clearly and labelled completely and correctly with no omissions of parts discussed in class. and even included the semicircular canals. In terms of the function of the parts of the ear, Bill had a confused conceptualization. On the final questions his description of what happened to the sound as it passed through the ear to the brain was less detailed than on the Ear Quiz. He correctly said that the eardrum vibrated in response to a sound and that the cochlea had tiny hairs that detected the pitch of a sound. He said correctly that the short hairs of the cochlea detected high pitched sounds, but he incorrectly stated that the ossicles help maintain balance. He did not describe the function of the ear flap or auditory nerve.

Over the course of this study, Bill shifted from a confused conceptualization (on the preview questions and ear design assignment) to a scientific conceptualization of the anatomy of the ear (on the Ear Quiz and final questions). Initially he had little idea of what the ear consisted of. On the Ear Quiz, he correctly labelled a diagram of the ear. On the final questions he provided a detailed and correctly labelled sketch of the ear. It seemed that it was an advantage that Bill originally had limited knowledge about the ear's anatomy. He was not strongly attached to his prior ideas and had little difficulty accepting and remembering the diagram of the ear that he was presented in class.

As the study progressed, Bill shifted from a confused conceptualization (on the preview questions) to a confused conceptualization of the functions of the parts of the ear (on the Ear Quiz and final questions). In terms of the function of the parts of the ear, on the preview questions Bill had little idea of what happened to allow sound to be detected by the brain. This was not surprising because the only parts he identified were the ear flap, eardrum and brain. On the test, he was able to describe the general function of each part of the ear, but he demonstrated confusion in his description of how the length of the hairs affected the pitch of sound they detected. Another indicator of confusion on the Ear Quiz was when he linked how sound travelled through the ear to the semi-circular canals maintaining balance. On the final questions, he correctly matched the length of the hairs in the cochlea with the pitch of sound they detected and described the function of the eardrum and auditory nerve. The evidence of confusion in his conceptualization was when he said that the ossicles maintained balance [rather than amplify the sound]. Overall, Bill's conceptualizations of the ear and hearing became more detailed following the conclusion of the sound unit to the end of the ear section. Despite some confusion, his conceptualization of the ear and hearing was appreciably more detailed on the Ear Quiz than on the preview questions. He retained this level of detail on the final questions.

The Ear: Causes of Deafness / Treatment -- Data

On the preview questions, Bill said that our sense of hearing was vital to us because it allowed us to avoid getting hit by large trucks on the highway because we could hear them in advance. He said loud noises such as those produced by airplanes were a cause of deafness. He added that loud sounds could "blow your eardrum." He said he would never leave his house if he became deaf. He thought the main purpose of learning about sound and hearing was to protect our sense of hearing.

On the Ear Quiz he said the main cause of hearing damage was loud noises which levelled the tiny hairs in the cochlea and could not be fixed. He said said that puncturing or damaging the eardrum was a major cause of hearing loss, but that the eardrum could repair itself. For how pressure changes affected our hearing, he said "our eardrum bends in when we go down and outward when we go up." During probing, he explained that when the pressure inside and outside the ear weren't balanced, the eardrum was pushed either in or out. He said a throat infection could cause hearing loss because it could creep up the eustachian tube and severely damage the ossicles.

On the final questions, Bill said that if your ear became plugged with gum, "you would not be completely deaf because the sound could slowly travel through the gum." For the question about the ossicles separating, he said "once they [the ossicles] are broken you are deaf." As two different major causes of hearing loss he listed: a punctured eardrum which is temporary hearing loss; and loud noises levelling the tiny hairs in your cochlea which is permanent hearing loss.

The Ear: Causes of Deafness / Treatment -- Discussion

Confused conceptualization

On the preview questions, Bill had a confused conceptualization of hearing loss and deafness. He correctly guessed that loud sounds were the main cause of hearing loss, but incorrectly said that loud sounds damaged the eardrum (rather than damaging the hairs of the cochlea). He did not list any other causes of hearing loss. It was no surprise that Bill could not explain correctly how the ear was damaged, because he had little knowledge of the ear's anatomy and how it functioned. At this stage of the study, he did not categorize hearing loss as either conductive loss or neural loss (and he was not expected to).

Scientific conceptualization

On the Ear Quiz, Bill's conceptualization of hearing loss and deafness approached a close match with the scientific perspective. As on the preview questions, he correctly stated that loud sounds were the leading cause of hearing loss, but this time he correctly said that loud sounds damaged the tiny hairs of the cochlea. He correctly identified other causes of hearing loss such as a punctured eardrum, or throat infections affecting the ossicles in the middle ear. He said that the eardrum could repair itself which is often the case. He successfully answered several other challenging questions. He explained how changes in altitude and air pressure affected the eardrum. He described how the eustachian tube connected the middle ear to the throat so that throat infections could reach the ossicles and damage the sense of hearing. The major omissions from Bill's discussion of hearing loss were that he did not categorize the damage to the cochlea as permanent and he did not list and categorize other causes of hearing loss such as birth defects, obstructions in the ear canal, and damage to the auditory nerve or the hearing area of the brain.

Confused conceptualization

On the final questions, Bill had a confused conceptualization of hearing loss and deafness. He correctly argued that if the ear canal became plugged with gum, the person would not be completely deaf because sound could still pass through the gum. For the ossicles separating he said the hearing loss would be permanent and the person would be completely deaf. He did not take into account that the sound might bypass the ossicles through the bones of the skull to reach the cochlea. He correctly categorized a punctured eardrum as likely a temporary hearing loss and damage to the hairs in the cochlea as permanent hearing loss. He did not distinguish between conductive hearing loss and neural hearing loss.

As the study progressed, Bill shifted from a confused conceptualization on the preview questions, to a scientific conceptualization on the Ear Quiz, and finally to a confused conceptualization of hearing loss on the final questions. Throughout the study he knew that loud sounds were a major cause of hearing loss. On the preview questions he could not explain how the ear was damaged because he did not know the anatomy of the ear. On the Ear Quiz and final questions he was able to explain how loud sounds damaged the ear. Bill provided more detailed and accurate answers on the Ear Quiz than the final questions to questions about how different causes of hearing loss damaged the ear. In sum, Bill started with limited knowledge of hearing loss, peaked on the test, and regressed on the final questions, but not back to the level on the preview questions.

General Discussion

Over the time of this investigation, Bill's conceptualizations of sound related topics evolved in several patterns. He had a scientific conceptualization of the relative speeds of sound and light throughout the study. For the topics of sound transmission, sound passing through the states of matter, echoes, frequency ranges and the anatomy of the ear, he shifted from a confused conceptualization on the preview questions to a scientific conceptualization on the sound test (or Ear Quiz) and the final questions. He moved from a confused conceptualization of causes of hearing loss on the preview questions, to a scientific conceptualization on the sound test, and finally a confused conceptualization on the final questions. For the topics of sound waves, frequency and pitch, and the ear's function, Bill started with a confused conceptualization on the preview questions to a confused conceptualization on the sound test (or Ear Quiz) and final questions.

It seemed Bill's prior ideas played a key role in whether ultimately he ended up demonstrating a scientific conceptualization or a confused conceptualization. An example of how his prior ideas led him to a scientific conceptualization was with the topic of echoes. His conceptualization of echoes on the preview questions echoes formed the basis for how he thought sound travelled and he recognized that echoes were rebounded sounds. He ended up with a clear conceptualization of both how echoes occurred and why their loudness diminished. An example of how his prior ideas led him to a confused conceptualization was with the topic of frequency and pitch. On the preview questions he thought that pitch and loudness meant the same thing. Althought he was able to remember definitions of terms associated with frequency and pitch, ultimately, his confusion between pitch and loudness carried through to the final questions. He continued to not distinguish between pitch and loudness and in answering questions about how the pitch could be changed he tended to discuss factors affecting loudness instead.

Bill exhibited a remarkable shift in his conceptualization of the ear's anatomy. Initially, he knew only that the ear consisted of an ear flap and eardrum that somehow transferred information about sound to the brain. On the test and final questions he knew all the parts of the ear and their sequence from the ear flap to the brain. This shift to a scientific conceptualization illustrated how much easier it was to influence a student's conceptualizations when the student started with limited prior ideas that he or she was not strongly attached to.

I had guessed incorrectly that he would have little success in generating scientific conceptualizations of many of the sound-related topics. I was particularly impressed by his conceptualizations of sound transmission and the ear's anatomy. He seemed to think about the observations of sound and hearing he made in his daily life and attempted to relate them to what he was being taught in class. It appeared that he had moved past the point of simple memorization and had processed the information in such a way that he was able to apply his knowledge to difficult questions. In sum, Bill surprised me pleasantly.