TRANSFER OF LEARNING FROM TRADITIONAL OPTICS

TO WAVEFRONT ABERROMTERY

by

DYAN L. McBRIDE

B.A., Edinboro University, Edinboro Pennsylvania, 2003
M.S., Miami University, Oxford Ohio, 2005

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Physics
College of Arts and Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2009

Abstract

This research presents an investigation of how students dynamically construct knowledge in a new situation. In particular, this work focuses on the contexts of light and optics, and examines the dynamic construction of an understanding of wavefront aberrometry.

The study began with clinical interviews designed to elicit students' prior knowledge about light, basic optics, and vision; the data were analyzed phenomenographically to obtain student models of understanding and examine the possible model variations. The results indicate that students have a significant number of resources in this subject area, though some are incomplete or less useful than others.

In subsequent phases, many learning and teaching interviews were conducted to design and test scaffolding procedures that could be of use to students as they constructed their understanding of the given phenomenon. Throughout this work, student responses were analyzed in terms of the resources that were being used through the knowledge construction process.

Finally, a modified analysis method is presented and utilized for quantifying what types of concepts students use while constructing their understanding, and how they are able to link varying types of concepts together.

Significant implications extend beyond the single context of wavefront aberrometry. Each distinct analysis technique provides further insight to the ways in which students learn across contexts and the ways in which we can scaffold their learning to improve curriculum and instruction.

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CHAPTER 1 - **Introduction**

This research project is a combination of two different yet associated driving forces: first, the desire to help students build conceptual knowledge and to successfully apply that knowledge in a wide range of contexts, and second, the shift in physics education research to go beyond misconceptions and study in more detail the ways in which students construct knowledge.

The remainder of this chapter provides an overview of the research study including the scope and rationale for the study, an overview of the research strategy, broader impacts of the study, and a description of the remainder of this dissertation.

1.1 Research Scope and Rationale

This work is funded by a grant from the National Science Foundation (NSF) entitled *Modern Miracle Medical Machines (MMMM).* The purpose of this project is two-fold. The first goal is to study student reasoning and models of understanding how physics topics apply contemporary medical techniques. The second goal is to develop hands-on, instructional materials that illustrate how contemporary physics topics can be applied to real-world medicine. The research and instructional materials are targeted for pre-med type students, or more generally for students in an algebra-based introductory level physics course.

This project addresses both goals of MMMM in that it focuses on researching how students learn and also has developed instructional materials that address wavefront aberrometry. These materials are portable in that they can be utilized in any classroom without disturbing the larger structure of the course, and they can either stand-alone or be used in combination with other MMMM instructional materials that have been developed by the Kansas State University Physics Education Research Group.

1.2 Research Questions

In the broadest sense, this study focuses on how students use their existing knowledge to develop models of the physical world around them. In particular, it seeks to determine how students use their existing knowledge to construct an understanding of a new context and to determine what scaffolding activities promote such learning.

In order to address these general issues, we have chosen the context of wavefront aberrometry. In this context, the following specific research questions guided this study:

- What resources do introductory-level students use to understand light and optics, and what variations exist between students' understanding?
- To what extent can students apply their knowledge of light and optics to construct an understanding of wavefront aberrometry, and what scaffolding activities can be utilize to aide their knowledge construction?

1.3 Research Strategy

The research questions listed above were addressed from the constructivist perspective. In this view, the process of learning is a dynamic one in which students must draw on their prior experiences to construct new knowledge. By accepting the constructivist perspective, one can observe the dynamic process that is learning and therefore study knowledge construction. The results of this type of research then enable us to help students learn physics better and more efficiently.

The study was conducted with a mixed-methodological approach that consisted of a blend of grounded theory and phenomenography. (These methods will be described in detail in Chapter 3.) The grounded theory approach first allowed us to study how students understand basic light and optics. This was achieved through the use of semi-structured clinical interviews, and led to the development of a set of scaffolding activities aimed at helping students achieve an ideal model of light and optics and the functions of the human eye.

Utilizing the phenomenographic approach allowed for the study of how students applied their prior knowledge to construct an understanding of the wavefront aberrometer and also specifically look at the models that students create and to elicit variations between these models. This second phase of the study was conducted using learning-teaching interviews which enabled us to see how students interacted with the scaffolding activities during their knowledge construction. Finally, an implementation phase was conducted in order to assure that the scaffolding activities were appropriate beyond the individual interview setting and to test the usability of the learning materials. Table 1.1 describes briefly each of the phases.

Table 1.1 Timeline of Research Project

Phase	Description	Timeline	Methodology
Planning Phase	Literature review, research plan	Fall 2005 – Spring 2006	---
Phase 1	Pilot study	Summer 2006 – Spring 2007	Grounded Theory
Phase 2	Two part interviews, eye and aberrometry	Fall 2007	Phenomenography
Phase 3	Individual and group interviews, post-instruction	Spring-Summer 2008	Phenomenography
Phase 4	Implementation in large-lab format	Fall 2008	Phenomenography
Dissertation	Preparing dissertation and finalizing analysis	Spring 2009	Phenomenography

1.4 Goals

This study involves a complex phenomenon and a context in which student understanding has never been studied. As such, one goal of this project was to study extensively what students are able to learn regarding wavefront aberrometry. From this information, an end goal of the project was to create a set of learning materials that students could successfully accomplish. As such, no ‘target model’ of student understanding was initially identified. However, the following ideas served as sub-goals which guided the exploration of student models of wavefront aberrometry. Further explanation of the physics of each of these goals can be found in section 2.8.2.

1. Understand how the grid pattern of a wavefront aberrometer is formed
2. Recognize how the grid pattern will change based on vision defects and aberrations
3. Understand how the grid pattern can be used for vision diagnosis

1.5 Impacts and Implications

The impact of this research extends beyond the directly studied contexts of light and optics and wavefront aberrometry. For the students who participate in the learning-teaching interviews, their participation in dynamically constructing knowledge of a new and rather high-tech phenomenon will prepare them better for thinking about science in terms of modern technology in the future. The ability to think critically and be scientifically literate is a skill that will extend far beyond the classroom or even a single profession.

For the researchers, this study will provide more insight into how student learn, use prior knowledge and experiences when trying to understand new phenomena, and construct models of new knowledge and experiences. This type of research also has a profound effect on the general process of teaching and learning. With continued research leading toward a better understanding of the student learning process, learning materials that better facilitate student understanding can be designed.

1.6 Layout of Dissertation

This dissertation consists of seven chapters and an appendix. Following this introduction, Chapter 2 provides a review of literature related to the study including the theoretical and pedagogical frameworks that guided this study. Because wavefront aberrometry involves some rather sophisticated physics, Chapter 2 also includes a review of the physics of wavefront aberrometry. Chapter 3 presents the methodological perspectives for the study, including a description of the research setting and tools and a basic outline of the project design. Each phase of the study is described in detail in Chapter 4, including the demographics and timeline of the study, as well as the basic protocol used during each phase.

Chapters 5 and 6 present the data analysis. Chapter 5 focuses on an analysis of the resources that students use throughout the knowledge construction process and contains data from all phases of the project. Similarly, an analysis of all phases is presented in Chapter 6, this time using a concept categorization analysis technique. This technique is explained more fully in the chapter, and the benefits and drawbacks of this relatively new analysis scheme are also presented.

Finally, Chapter 7 addresses the research questions based on and supported by key findings from each phase of the study. It also provides a conclusion for the study and implications for future research, curriculum development, and instruction.

At the end of this dissertation is an Appendix which contains all of the protocols that were used throughout this study.

CHAPTER 2 - **Review of Related Literature**

This chapter provides an overview of literature related to this study. The first part of this chapter focuses on the literature supporting the framework of this study. Because constructivism is a foundational principle in this study, it is discussed in some detail, along with its different forms. Next, the literature relating to student models of understanding and conceptual change is surveyed. Transfer of learning is deeply imbedded in the goals of this investigation, and a discussion of both traditional and contemporary views on transfer are included.

The second part begins with a review of prior studies conducted to investigate student understanding of related physics concepts, particularly focusing on student ideas about light and ray optics and concludes with wavefront aberrometry, including a discussion of the physics concepts associated with the procedure.

2.1 Constructivism

There are two well-known theories of learning exist – behaviorism and constructivism. This research is conducted in the constructivist model of learning. Constructivists believe that learning is the construction of new knowledge from experiences and interactions. In this model of learning, the teacher takes on the role of facilitator, creating appropriate experiences for students that facilitate the process of knowledge construction. The constructivist perspective is important to this study in that it allows for the examination of the dynamic process that is student knowledge construction; it serves as the foundation for all protocols, scaffolding, and analysis throughout the study.

Though there have been many constructivist thinkers over time, Jean Piaget and Lev Vygotsky each proposed an interesting theory of constructivism that is particularly relevant to this work. While the two theories are in some ways distinctly different, there are also similarities. The first and perhaps most important similarity is that each assumes that knowledge acquisition is an active process. The differences lie in whether that process occurs within the realm of the individual learner, or in the context of the larger society. As postulated by Cobb, this research project was conducted under the assumption that these two theories of constructivism are not mutually exclusive but instead asserts that each brings its own value when examining the learning process (Cobb, 1994).

2.1.1 Piagetian Constructivism

Piaget discovered that there are four stages of cognitive development, and found that learning and knowledge occur differently in the stages. Piaget initially associated each of the four stages with a specific age group; however, the neo-Piagetian approach retains the idea of development stages while no longer associating them with a specific age range (Case, 1992). The first stage, the sensorimotor stage, is characterized by the demonstration of knowledge through actions, or motor activity, and is a stage in which knowledge is constantly evolving with each new interaction, as would be experienced by a young child. The second stage, known as the pre-operational stage, is one in which language and the use of symbols develops along with memory, but thinking lacks logic. In the concrete operational stage, logical and systematic manipulation of words and symbols develops, yet knowledge is limited to those objects which are concrete. Knowledge of abstract concepts is demonstrated in the fourth and final stage, the formal operational stage (Piaget, 1964).

The other concept important to Piaget was the idea of *schema*. A person's schema is essentially the foundation that is used to build a mental representation of the world. The schemata can be rearranged, reorganized, and further developed as the individual obtains more information about the world. The goal of the restructuring is to achieve what Piaget calls *equilibration*, and this restructuring occurs through the process of *adaptation*. *Equilibration* is required when the learner encounters something that is not familiar and cannot be explained by the current schema. This point of disequilibrium is often referred to as cognitive dissonance (Festinger, 1957). At this point, the schema must be adapted to apply to the new situation. One method of adaptation is *assimilation*, which occurs when the new knowledge is incorporated into the schema without the necessity of reorganizing the existing schema. However, the other method, *accommodation*, occurs when the existing schema must be modified to allow the new information to be resolved. This accommodation process is what Piaget refers to as the true process of learning (Piaget, 1964).

This research focuses to a large extent on the process of accommodation, in that the focus is on how students are able to modify their mental representations to include new situations and ideas. Because the situations provided to the student are unlike most things they had learned before, particularly the concepts of wavefront aberrometry, the students were not able to rely simply on assimilation to make sense of the new experiences. This research in no way assumes that learners are functioning in a particular stage of cognitive development. However, the experiences provided to participants have the potential to assist them in evolving from concrete to formal operational stages.

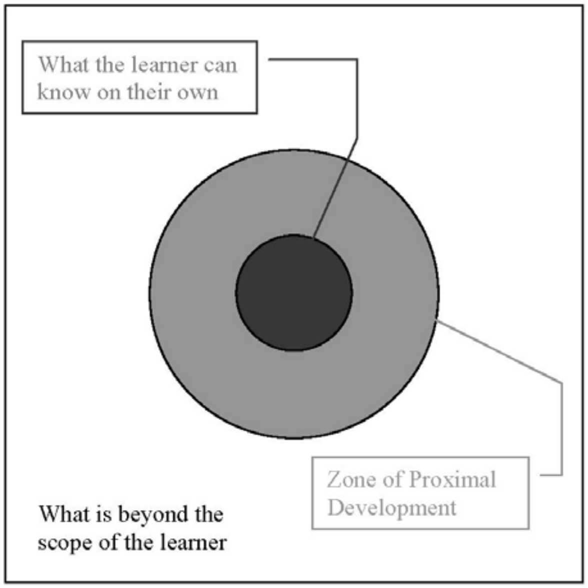
2.1.2 Vygotskian Constructivism

Whereas Piaget focused largely on the processes of individual learning, Vygotsky asserts that learning arises from social interactions that occur with teachers, fellow students, or even society as a whole (Vygotsky, 1978). His key postulate is the existence of a *Zone of Proximal Development* in which learning occurs. The Zone of Proximal Development (ZPD) is essentially the body of information that a person can learn at a given time. This region is also the boundary between what the learner can accomplish on his/her own and what can be learned with the help of a more knowledgeable other. A convenient representation can be found in Figure 2.1. If material that falls short of the ZPD is presented, the learner can achieve understanding on his/her own; if material is presented that is beyond the ZPD, the leaner cannot achieve understanding even with the help of others. As the learner progresses, the range of information he/she can learn on their own expands, as does his/her ZPD. In this respect, the ZPD is a dynamic range that changes as learning continues.

One method in which a more knowledgeable other can assist a learner is through the use of scaffolding (Bruner, 1966). Scaffolding consists of the experiences, supporting information, and assistance provided systematically to the learner. The scaffolding technique was implemented during the learning/teaching interviews conducted in this study, and included hands-on activities and computer simulations as well as questions and prompts from the interviewer/researcher.

The implications of the notion of a ZPD directly relate to the design of instructional materials: if the information presented to the student is beyond their ZPD, it should be expected that they will not successfully learn the material. However, if it is too far inside the ZPD, the student will not be challenged. This study makes no effort to quantify or measure the ZPD in any way, but simply asserts the importance of recognize such a region of learning ability.

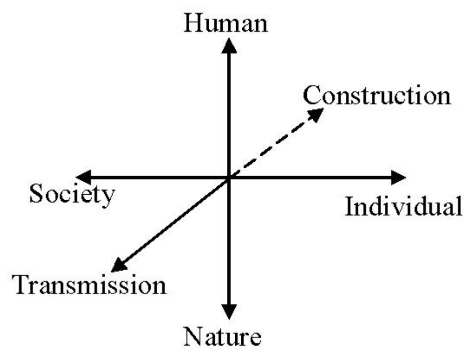
Figure 2.1 Representation of Vygotsky's Zone of Proximal Development



2.1.3 Philips' Dimensions of Constructivism

To represent the different facets of constructivism, Philips (1995) proposed a system of three-dimensions. The three dimensions are “individual psychology versus public discipline”, “humans the creator versus nature the instructor”, and the second deals with the fact that “activity can be described in terms of individual cognition or else in terms of social and political processes”. One convenient way to represent these dimensions of constructivism is by a simple three-dimensional axis system, as seen in Figure 2.2. These dimensions are presented as orthogonal, but it is not meant to indicate that they are mutually exclusive or independent; rather they form a continuum. The first axis, *individual versus society*, deals with the ownership of knowledge. At the individual end, individuals construct their known knowledge through their own interactions; at the society end, the focus is on how communities construct and share their combined knowledge. In this respect, both Piaget’s and Vygotsky’s work focuses on the individual component. The second axis, *human versus nature*, deals with the creation of knowledge. Human constructivists believe that knowledge is a construct of the person, and therefore only exists inside the human mind. Nature constructivists, on the other hand, believe that knowledge is always present and simply waiting to be absorbed. Finally, the third axis, *construction versus transmission*, focuses on the process of learning. Both Piaget and Vygotsky treat knowledge as something that must be actively created by the individual, and therefore focus on the construction component. Proponents of transmission feel that knowledge is passively obtained by the learner, and yet still internalized.

Figure 2.2 Representation of Phillips' dimensions of constructivism



For the purposes of this study, constructivism will be considered from an individual, human, construction point of view. However, the societal component will also be considered in the context of group work and group interviews, allowing for knowledge to be seen from the point of view of an actively engaged individual who is constantly interacting with the environment.

2.2 Models of Student Reasoning

Following the path laid by Piaget and his description of schema, many physics education researchers have attempted to describe the structures of knowledge. Description of the structures of knowledge allow for further investigation into the processes of learning, specifically by investigating how the knowledge structures are put to use. Particularly in the last several years, the focus of physics education research has shifted away from studies about student difficulties and alternative conceptions on various physics concepts, instead focusing on examining how students construct their understanding and use their prior knowledge and experiences when trying to understand physics. In these types of studies, the structures of knowledge become a key factor for gaining insight into student learning.

The primary focus of this project is to study knowledge construction, and thus considered in this section are three different knowledge structures, each of different grain-size. Each of these knowledge structures are important to this study in that student knowledge construction can be examined in terms of what type of structures are used.

2.2.1 Phenomenological Primitives

In trying to describe how students use their intuitive knowledge in the context of physics, diSessa (1993) proposed a small knowledge structure: phenomenological primitives (p-prims). P-prims are the smallest and perhaps simplest grain-size of knowledge, and are applicable in a wide range of contexts and situations. The name phenomenological primitive is significant because it classifies these structures as simple, concrete, and derived from the observations and experiences of the individual.

Some examples of p-prims from diSessa's work are:

- *force as a mover:* things move in the direction they are pushed
- *dying away:* for example, moving objects coming to rest without a clear cause
- *canceling/dynamic balancing:* as when forces are arranged so as to create an equilibrium condition

diSessa emphasizes that p-prims cannot be classified as correct or incorrect, rather that they can be used correctly or incorrectly depending on the circumstance. For example, the idea of *force as a mover* works well as the student applies it in everyday life – one must continue pushing a shopping cart for it to keep moving. However, when applied in the context of a physics class, perhaps when learning Newton's Second Law, the idea of *force as a mover* can lead the student to some very incorrect conclusions.

2.2.2 Resources

Hammer uses the term 'resource' to describe in general the different constructs that students use when constructing their knowledge (Hammer, 2000). Resources may be of varying grain-sizes, though they are still small in that they do not constitute a complete model. Instead, resources can be thought of as a piece of "raw intuition" (Hammer & Elby, 2002) that can be applied in a wide range of situations. Resources include a range of phenomenological, epistemological or procedural concepts. Like p-prims, resources cannot be labeled as correct or incorrect; instead, the activation of appropriate resources for the given context or situation is important. The activation/association of resources can easily be tied into the transfer of learning framework that will be discussed in the following sections.

Of interest are also the epistemic resources, or epistemic modes, which are a part of any students' resources. Hammer and Elby list several possible epistemic resources, three of which are explained in detail: "knowledge as propagated stuff", "knowledge as free creation", and "knowledge as fabricated stuff". When using the resource that knowledge is propagated stuff, a student considers knowledge to be the stuff that is passed-on from parents, teachers, or even textbooks. When in this mode, a student would be likely to explain that an answer is true because 'the teacher said so.' When the resource that knowledge is freely created is being used, a student considers imagination to be the impetus behind the answer/explanation. The resource that knowledge is fabricated stuff allows the student to see one piece of knowledge as being developed from other knowledge, and allows for a formation of concepts from each other. These resources are not hierarchical, and may be applied in different contexts and at different levels of sophistication.

Along with the identification of resources, Hammer *et al.* (2005) assert that one must also consider the context in which the resources are activated, as well as how the student frames the situation. The way a student interprets a given task or situation is known as 'framing'; two different students could potentially frame the same situation in very different ways. For example, if a student frames the situation as one in which knowledge must be given by authority, the student will likely be hesitant to create and test new ideas. In this respect, the way that the student frames a situation can have a large affect on what resources are activated or deactivated, and must be carefully considered along with the resources themselves.

Figure 2.3 Association diagram for resources, from (Redish, 2003)

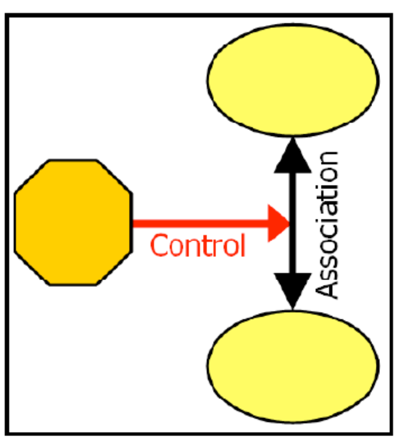


Figure 2.3 shows an association diagram. The two round bubbles can be thought of as the resources which students utilize when constructing an understanding; perhaps a piece of prior knowledge, as well as a bit of information that has been readout from the new context. Whether or not these associations are created, and how they are created, is determined by a set of controlling factors. These controlling factors may include the epistemic mode the student is operating in and how the student frames the current situation.

2.2.3 Facets

Minstrell suggests another knowledge structure – the facet. A facet is a knowledge structure that is relatively small, but focuses on a specific topic instead of being an abstract structure such as a p-prim (Minstrell, 1992). Like p-prims or resources, facets can be classified as either correct or incorrect. Redish explains that facets come from the mapping of the abstract structures (p-prims) onto the many diverse situations of the physical world (Redish, 2003).

Minstrell also suggests that by studying the facets used by students in different contexts, effective learning strategies can be created. In particular, he suggests that a facet that is not applicable is a certain situation can be used as a bridge to a more applicable facet. He uses the term *anchoring conception* to refer to that starting place, and helps guide the student toward activating applicable facets through a series of *bridging analogies* (Minstrell, 1982). Minstrell uses the example of getting students to understand the normal force. The anchoring conception in this case is an understanding of springs – through a series of bridging analogies, the student is led to think of the table as being composed of microscopically small, very stiff springs – which allows them to appropriately form a facet about the normal force. Such bridging analogies are potentially useful in designing activities for scaffolding student understanding.

2.2.4 Coordination Classes

A much larger grain-size knowledge structure is a coordination class, as proposed by diSessa and Sherin (1998). A coordination class is a set of strategies that are systematically connected. This connected set of strategies allows the student to gain and process information from the world around them. Coordination classes are complex systems, but can be considered as having two different components: a *readout strategy* and a *causal net*. The readout strategy is the part of the structure that allows the student to gain information from the world and translate it into meaningful pieces. The causal net is the activated to draw inferences about that meaningful information. Just as how a student frames a situation can affect which resources are activated, the way that he/she reads-out information from a situation will change the way he/she draws inferences about the situation.

Because of their complexity, coordination classes can be much more difficult to identify than the smaller grain-size structures such as p-prims. Two possible difficulties that students might incur while constructing their coordination class is *span* and *alignment* (diSessa & Wagner, 2005). Span deals with the breadth of knowledge: it examines across what contexts the student can apply their coordination class. Alignment deals with the read-out strategy: it considers whether the same information is read-out from a variety of similar situations. Considering how a student reads-out information from different circumstances leads to a better understanding of they will react to the provided scaffolding activities.

2.2.5 Mental Models

Many researchers have proposed different theories of students' mental models, a much larger grain-size knowledge structure. The study of mental models spans both education and cognitive psychology. Some explanations of mental models are as follows:

- "mental models are structural analogues of the world as perceived or conceptualized" (Johnson-Laird, 1983)
- "[mental models] are related to human knowledge of the world and how it works" (Gentner & Stevens, 1983)
- "[mental models] are a representation of a target, which might be an object, even, process, or system" (Gilbert & Boulter, 1998)
- "mental models refer to a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning" (Vosniadou, 1994)
- "[mental models are] the collection of mental patterns people build to organize their experiences related to a particular topic" (Redish, 1994)

The vast range of theories and descriptions of the term mental model make the use of "mental models" in a research study exceedingly difficult. Also, as described by Greca and Moriera, students' mental models are internal representations that can change over time (2002). From this perspective, the mental model that an education researcher suggests a student may have is truly just the researcher's model of how a student may be understanding a particular topic, that the researcher gathered from the students' expressions of their model.

2.3 Transfer of Learning

The study of transfer is one that has been evolving for a few decades. The earliest studies of transfer focused primarily on examining if and how students were able to apply previously learned problem solving techniques in new but structurally similar situations (Bassok, 1990; Brown, Bransford, Ferrera, & Campione, 1983; Brown & Kane, 1988; Z. Chen & Daehler, 1989; Lockhart, Lamon, & Glick, 1988; Nisbett, Fong, Lehman, & Cheng, 1987; Novick, 1988; Perfetto, Bransford, & Franks, 1983; Reed, Ernst, & Banergi, 1974). Structural similarity in this case was defined from the expert's viewpoint. Researchers assumed that because two problems were structurally similar, students would be able to identify the similarities and therefore be successful at solving the problem despite the differing contexts. Researchers found that, using this definition, transfer was exceedingly rare. An example of such structurally similar problems is the "fortress vs. tumor" problem (Glick & Holyoak, 1998). In this situation, the students first read a story about an attack on a fortress. In this story, the general must lead his army in small sections down each of the available roads and meet at the fortress simultaneously to win the battle without destroying the small surrounding towns. Afterwards, the same students are presented with the task of destroying a tumor inside a human body, and asked to find a solution which minimizes the destruction of healthy tissue. As expected, only approximately ¾ of the participants were able to solve the tumor problem.

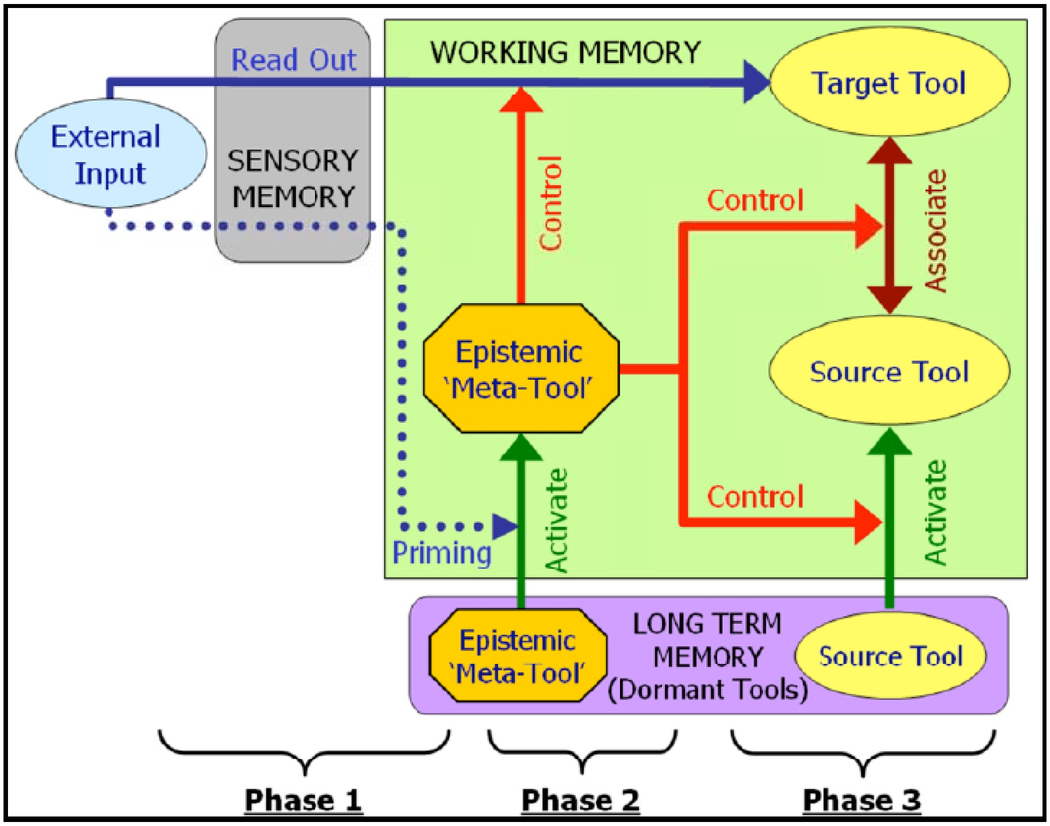
More contemporary perspectives on transfer have emerged in the past decade, however. These contemporary perspectives shifted away from identification of similarities that, according to experts, should transfer. Instead, researchers began observing any and all knowledge that could potentially transfer to a new situation. Based on the idea of situated learning (Lave & Wenger, 1991), Lobato presented what she dubbed an "Actor-oriented" view of transfer – this allowed for similarities to be defined by the student instead of the expert (Lobato, 1996). As others continued forward with this broadened definition, transfer became thought of as being universal – everyone transfers some information into every new situation.

Realizing that a learner is not isolated from the environment, Greeno and colleagues began to consider the social and cultural aspects of learning and how learning is transferred. The focus was on three different aspects: *attunement to affordance*s, *potential states of affairs*, and *affordances for reasoning* (Greeno, Moore, & Smith, 1993). Greeno *et al.* define affordances as the support for activities and materials in a given situation; abilities refer to characteristics that allow for the activity. To illustrate this rather complex point, Greeno *et al.* use the example of a doorway. In many situations, the doorway "affords" the activity for walking through it. Through social interactions, we learn when the action of walking through the doorway will create a desired end-result, and therefore learn to be attuned to that opportunity. The potential states of affairs refers to a person's ability to realize what a situation could potentially hold, even if it currently does not. Using the same illustration as before, realizing the potential state of affairs would be to see another person standing near a doorway, and realizing that he/she is able to use the doorway, even though he/she may or may not choose to. Finally, affordances for reasoning deals with a person's ability to make inferences based on the current situation. In the view of Greeno, *et al.*, all of these aspects create a view of transfer that is rooted in social and ecological settings instead of mental representations or constructs.

Bransford and Schwartz look at transfer as being a measure of how prepared students are for future learning endeavors; they discuss evaluation as being either *sequestered problem solving*, which measures the traditional transfer, or *preparation for future learning*, which allows for the measurement of transfer from a more contemporary stance (Bransford & Schwartz, 1999). They also describe a difference between information that is *transferred into* and *transferred out* of a given situation, and highlight a need to examine transfer in both the learning and application contexts (Schwartz, Bransford, & Sears, 2005).

Rebello and colleagues emphasize the need to describe transfer from the perspective of the student instead of the researcher/expert. In this perspective, transfer is a dynamic process in which the students create associations between pieces of knowledge to understand some target phenomenon. Because they are in a new situation, the students must create associations between pieces of their preexisting knowledge structure and the new information that they are obtaining from their environment (Rebello, et al., 2005). In the same work, Rebello *et al.* propose a model of transfer which can be seen in Figure 2.4. This model shows how associations are created between existing knowledge and new information in the working memory, and how these associations are controlled by factors both internal and external to the learner.

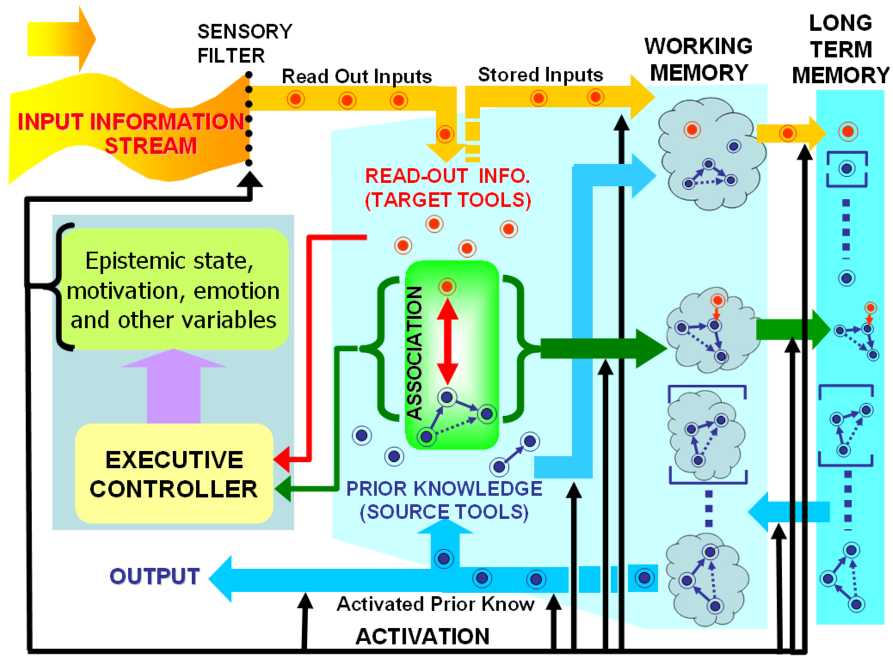
Figure 2.4 Model showing a snapshot of transfer from Rebello *et al.* (2005)



As an expansion of the static framework, Rebello presented the more dynamic model shown in Figure 2.5. In this model, the mediating factors are highlighted to show the many paths that knowledge creation can take. The read-out information is filtered out from new information and also controls whether an association is made and if it is stored in the working or long term memory or is given as an output, such as an answer to a question. Though more complicated, the model is more comprehensive in that it highlights the controlling factors and feedback mechanisms at each stage of knowledge construction.

This work adopts the contemporary viewpoint of transfer and seeks to consider all prior knowledge and information that students use when constructing new knowledge. Further, this study primarily adopts the framework presented by Rebello *et al.* and seeks to understand what associations students create and what factors influence these associations.

Figure 2.5 Dynamic transfer model highlighting feedback loops influencing transfer from Rebello (2007).



2.4 Conceptual Change

Much of the work done on conceptual change derives from Piagetian constructivism which is heavily adopted in this study and therefore has great relevance. The following are examples of the conceptual change literature that are the most pertinent to this study.

Posner and Strike (1982) describe conceptual change research as having two central goals: to uncover preconceptions about particular topics in physics and to test methods of helping students to change their conceptual framework about those topics. As illustrated by the works of McDermott and Redish (1999) and Duit (2007), a large body of work focuses on the former goal, and an ever-increasing number of studies are conducted on the latter.

As described in section 2.3, Piagetian constructivism asserts that learning occurs because of the experiences of the individual, and that a cognitive dissonance, or cognitive conflict, can be the impetus for the restructuring of schema and therefore learning. According to Posner and Strike, this process can be the motivation for conceptual change. Park (2006) proposes that students can use similarity-based reasoning while attempting to resolve their cognitive conflict. This similarity-based reasoning allows students to map their prior knowledge onto the new situation – a notion that is consistent with the dynamic transfer framework utilized in this study. Also consistent with the dynamic transfer framework and the identification of resources as a method for studying transfer are results of a study by Vosniadou and Brewer (1992), in which they found that even young children showed evidence of a 'framework theory', which identified ontological and epistemological assumptions that students utilized subconsciously while they were discussing properties of the Earth.

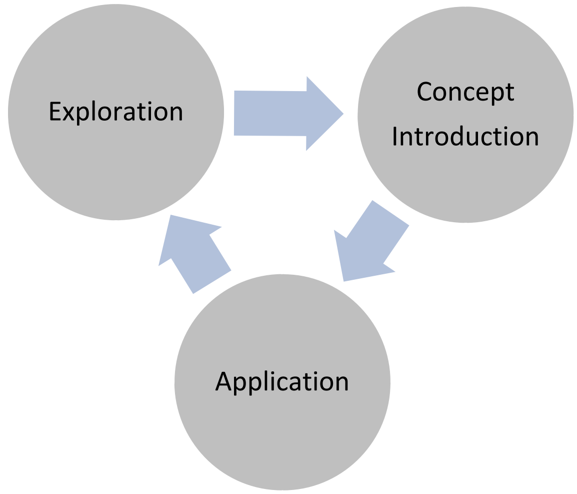
Different theories on the process of conceptual change have been proposed over the last two decades. Conceptual change can be viewed as the process of 'repairing misconceptions', where students must first identify their misconception and be challenged to construct a new, correct conception (Chi & Roscoe, 2002). Others feel that conceptual change is a gradual process in which students' intuitive frameworks are reorganized in a synthesis process of mental models (Vosniadou, 2002). Yet others see conceptual change as an organization of already-present but fragmented knowledge into coherent and complex knowledge systems (diSessa & Wagner, 2005). This work assumes that conceptual change can occur from a variety of mechanism, and that the above processes are not necessarily mutually exclusive.

Posner recommends the following conditions for inducing conceptual change: the student must be dissatisfied with their current ideas, the new idea should make sense to the student, the new idea should seem plausible to the student, and finally, the new idea should be applicable for the student in a variety of other situations. In aligning with these recommendations, this research attempts to meet all of Posner's recommendations. Also, the scaffolding provided to the students is varied in such a way as to present different components of proposed conceptual change theories such as hands-on activities and providing discrepant events/cognitive dissonance (Posner & Strike, 1982).

2.5 The Learning Cycle

Karplus' Learning Cycle is a research-based approach to designing curricula that focus primarily on student reasoning (1977). The cyclic nature of the approach is highlighted in Figure 2.6.

Figure 2.6 Representation of Karplus Learning Cycle



In the first part of the cycle, students are asked to *explore* phenomena relevant to the target knowledge. This can occur through hands-on activities, visualizations, or even discussion of real-world phenomena. After this initial exploration, students are presented with a *concept introduction* in which the content knowledge is presented and the exploration activities serve as a focal point for the explanations. Finally, students are asked to *apply* their newly acquired knowledge in a range of contexts and situations.

Many adaptations of the Learning Cycle have been proposed, including the Modeling Cycle (Wells, Hestenes, & Swackhamer, 1995). In the Modeling Cycle, students are asked to create a model during the Model Development phase, and then engage in Model Deployment. The Model Development phase can be thought of as mapping onto the Exploration and Concept Introduction phases of the Karplus cycle, while Model Deployment aligns with the Application phase.

2.6 Concept Categorization Analysis

This section focuses on the literature relevant to a newly-refined analysis technique that is presented in Chapter 6 of this work. While it does not directly answer the two formal research questions, this analysis technique emerged from the data collected for this study and provides a new and interesting basis for examining student understanding.

2.6.1 Concept Categorization

In 1947, F.S.C. Northrop published a book with the purpose of exploring the notion of logic and how it is applied in the sciences and humanities. In this work, he postulated that concepts require an assigned meaning, and that they can be divided into two types based on how the meaning is assigned. The first category is *concepts by intuition*, and is so named because the concepts' meaning is immediately realized. The second type, *concepts by postulation*, Northrop (1947) describes as having a meaning "which in whole or part is designated by the postulates of the deductive theory in which it occurs" (p. 83). As an example, consider the notion of 'work.' As defined in the context of physics, work is equal to the scalar product of force and distance (a concept by postulation). Thus, a person who holds a heavy object at the same height for a considerable length of time would be doing no physical work. However, in common language, he/she would likely argue otherwise – work in that context is somehow correlated to the effort exerted (a concept by intuition).

Following Northrop's work on how students construct meaning, Lawson, Abraham and Renner (1989) presented a framework for classifying concepts. The work of Lawson and colleagues was done in the context of biology, and as such all examples given are within the realm of biology. The first proposed type is *concepts by apprehension*, which are those that have an immediately sensed input. Lawson, *et al*. give the examples of cold, sharpness, and hunger. These concepts are felt and understood based on previous experience – if you've been cold once, you will immediately recognize the sensation of coldness again. *Descriptive concepts* seem equally as basic at first glance – objects such as table, processes (eating), and relationships such as before or beside are descriptive concepts. Though these concepts may be considered common-sense because of how deeply they are engrained, they must be learned through a series of interactions with the world. Finally, *theoretical concepts* are the highest level of concepts, and serve the purpose of explaining causal events. Lawson, *et al*. explain that theoretical concepts are those that require some sort of imagination or assumptions, and include ideas such as ghosts or magic.

Law *et al.* also describe *conceptual systems*, which are networks of different types of concepts, and classify them in two types: descriptive or theoretical (Lawson, et al., 1989). *Descriptive conceptual systems* are made up of concepts by apprehension and descriptive concepts only. They include no theoretical concepts, and therefore no explanation for causal events that cannot be readily perceived. Lawson *et al.* give the examples of human anatomy (because of its descriptive and non-explanatory nature) and the game of baseball. *Theoretical conceptual systems*, on the other hand, include theoretical concepts as well. They provide explanations for causal events, such as in atomic theory and the theory of evolution.

While all three types of concepts are necessary in order for a complete categorization, Lawson asserts that concepts by apprehension seem to offer no meaningful contribution to understanding how students use prior knowledge (existing concepts) in new contexts and situations. Thus, further works by Lawson and colleagues focused primarily on descriptive and theoretical concepts. In addition, developmental theory including intellectual development was utilized to examine what types of concepts were exhibited by learners at different stages (Lawson & Renner, 1975; Lawson & Thompson, 1988).

In a more recent study, the types of concepts were refined and a third type of concept – *hypothetical concepts* – was proposed in order to revise the categorization system, and the definitions of descriptive and theoretical concepts were also refined (Lawson, Alkhoury, Benford, Clark, & Falconer, 2000). As described by Lawson using the refined definitions, descriptive concepts are the most basic and easiest to learn. Descriptive concepts are those that are easily and directly observable. Some examples cited are food chain, carnivore, and nocturnal. Theoretical concepts remain the most advanced level of concepts as they are the most difficult to learn, as they cannot possibly be observed in any circumstance. Molecules, air pressure, genes, and osmosis are listed as examples of theoretical concepts (Lawson, et al., 2000). Along with these two, they proposed a new and intermediate type of concepts – hypothetical concepts. Hypothetical concepts are of a higher level than descriptive concepts, and as such are more challenging to learn. Hypothetical concepts are those that are not directly observable, but that one could imagine observing if it was possible to watch for an extended period of time. Some examples presented of hypothetical concepts are fossils, natural selection, and evolution.

2.6.2 Meaningful Understanding

Ausubel characterized the distinction of meaningful versus rote learning in terms of the value of the knowledge. Ausubel asserts that for the learning to be meaningful, the learner must be disposed to relating the new learning to something he/she already knows, and that the learning is potentially significant to the learner, and not simply arbitrary information (Ausubel, 1977). In this perspective, a central tenant in meaningful understanding is therefore the ability for a student to use those meaningfully-learned concepts (prior knowledge) in a new situation which therefore aligns well with the goals for this study.

Using Ausubel's definition of meaningful learning as a basis, Nieswandt and Bellomo expanded upon Lawson's work to analyze meaningful understanding of evolution in a 12th grade biology class (Nieswandt & Bellomo). By looking at not only what types of concepts students utilized but also what types of connections were made between concepts, Nieswandt and Bellomo proposed that they could examine written answers to extended-response questions to assess the level of meaningful understanding students displayed in the subject of evolution. They examined the following types of connections: one-concept-level links such as descriptive-descriptive or hypothetical-hypothetical, cross-concept-level links such as descriptive-hypothetical and hypothetical-theoretical and multi-concept-level links which connected all three types of concepts. Nieswandt and Bellomo postulate that true meaningful understanding is the ability not only to select and retrieve the necessary concepts, but to link those concepts together appropriately. For their analysis of the student responses, they compared student responses to the correct or expert response to determine whether students were able to select and link certain pre-determined concepts. Their results indicated that students did not create enough links to demonstrate the level of understanding expected in the correct answers (Nieswandt & Bellomo, 2008).

2.7 Previous Studies on Student Understanding

Research has been conducted on student conceptions of light and optics with students of several ages – from elementary school through college – and in countries all across the world. Because it would be impossible to present all of the literature that exists on this topic, the following sections present a representative sample of what has been done in the field. The first part focuses on the physics concepts of light and optics; this literature is useful because in order to understand how students form an understanding of vision and vision diagnosis, it is necessary to examine how students handle more fundamental concepts such as light and lenses. The nature of wavefronts requires some examination of physical optics, though the wavefront aberrometer can successfully be understood using only geometric optics. The second focuses on proposed methods for teaching these same concepts.

2.7.1 Research on Student Understanding

Light

Numerous studies have been conducted to address the question of how students understand light. Though we have constant, everyday experiences with light, researchers have shown that young students do not have a consistent understanding of the physical properties of light. For example, Andersson and Karrqvist looked at the notion of light as existing as physical object (Andersson & Karrqvist, 1981), Stead and Osborne investigated the perception of light traveling different distances at night than during the day (Stead & Osborne, 1980), and LaRosa (LaRosa, Mayer, Patrizi, & Vicentini-Missoni, 1984) and Watts (Watts, 1985) examined children's perceptions in terms of the medieval ideas of light being either 'lux' or 'lumen'. In each of these studies, the primary focus was the student conception of light with regard to the specific topic.

At the upper-level high school and undergraduate levels, research has also been conducted on how students understand and apply the basic concepts and physical properties of light. Galili studied post-instruction high school students and particularly focused on the idea of light flux. He suggested that many student difficulties, such as field-of-vision difficulties, could be addressed by including the flux concept of light in traditional instruction (Galili & Lavrik, 1998). While in the process of revising a 10th grade geometric optics course, Langley *et al.* conducted research that showed that while students have some familiarity with optical systems, they were confused by a unified model of optics when the context of sight was discussed (Langley, Ronen, & Eylon, 1997). Saxena focused on Indian secondary school students, and found that while they could seemingly understand the basic properties of light, they were unable to apply that knowledge to real situations (Saxena, 1991). While studying prospective elementary teachers, Bendall *et al.* found that they were unable to successfully complete tasks that focused on the propagation of light (Bendall, Galili, & Goldberg, 1993).

Lenses and Ray Optics

A separate and yet equally large body of literature exists on student understanding of lenses and ray optics. In one study, Goldberg and McDermott found that students had two major barriers to understanding how images were formed by a plane mirror: the first is the belief that an image can only be seen if it lies along the line-of-sight of the object, and the second is a lack of understanding of where the observer is located with respect to ray diagrams (1986). In a later study, they examined student conceptions dealing with images formed by converging lenses (Goldberg & McDermott, 1987). They found similar difficulties with interpreting ray diagrams, the role of the observer, and a dependence on naïve conceptions of light even in post-instruction participants. One famous component of this study is the idea of blocking half of a converging lens – many students will indicate that the result will be half of the image disappearing. Galili *et al.* found a similar result, calling students' conceptualization of image formation a "projected-image conceptualization … a hybridization of their pre-instruction holistic conceptualization and the formal physics conceptualization" (Galili, Bendall, & Goldberg, 1993).

Physical Optics

The body of literature on student understanding of physical optics is much smaller than for geometric optics. However, Ambrose and colleagues at the University of Washington conducted studies on student understanding of some wave phenomena of light. One study focused on the formation of diffraction and interference patterns, and found that students had difficulty knowing whether to apply geometric or wave optics, and as such often incorrectly applied pieces of each (Ambrose, Shaffer, Steinberg, & McDermott, 1999). They also found student difficulty in understanding the nature of photons. In a later study, they postulated that their previous findings could be a result of a lack of deeper understanding of the nature of electromagnetic waves in general, and as such went on to conduct numerous studies examining student understanding of the nature of electromagnetic waves (Ambrose, Heron, Vokos, & McDermott, 1999).

2.7.2 Research on Methods of Teaching Light and Optics

Proposed activities for teaching optics

Based on the volume of literature about student difficulties with light and optics, it is no surprise that the literature also contains a great number of articles about how and when optics should be taught. The following are just a sample of ideas, chosen with the intention of highlighting the wide range of ideas that exist.

To deal with the difficulties that arise because of the use of ray diagrams, one suggestion is to use many rays, and therefore highlight the notion that light spreads out in many directions from a single point (Grayson, 1995). Following previous work on designing *Tutorials in Introductory Physics* (McDermott & Shaffer, 2002), Wosilait *et al.* created a research-based tutorial that focuses on light and shadows (Wosilait, Heron, Shaffer, & McDermott, 1998). The tutorial is designed such that students start out with observations and progressively build a model which allows them to explain and predict physical phenomena. The Active Learning in Photonics and Optics (ALOP) program is an initiative designed to promote the inclusion of optics in introductory physics courses through teacher training, providing hands-on experiments for the students, and encouraging innovative teaching practices (*ALOP Asia*, 2006).

Other works have used optics as a context for studying teaching methods in general. The utilization of history is illustrated by Galili, where he showed that including historical ideas and conceptions of light and optics in with the usual curriculum produced positive changes in students' views of science while causing no detriment to content knowledge (2001). Also, Stephenson and Warwick demonstrated the utility of concept cartoons for eliciting alternative conceptions about light, encouraging discussion and resolution of ideas, and in some cases, even student metacognition (2002).

Computer Simulations

A subsection of the above proposed activities include the extensive use of computer simulations for teaching light and geometric and physical optics. Beginning as far back as 1987, personal computers were being used to assist in the teaching of optics. The proposed benefits included a vivid visual representation, the ability to continue examining phenomena outside of a laboratory setting, and the shorter time frame in which the concepts could be displayed (Chen, Huang, & Loh, 1987). As personal computers became more accessible, research-based software began to appear. Eylon *et al.* created a learning environment known as RAY with features such as ray-tracing and graphic tools (Eylon, Ronen, & Ganiel, 1996). In a research study using RAY, they found that while using the simulation improved how often students used the ray model of light correctly, it did not have a significant effect on measured conceptual understanding of light as a whole. Goldberg and Bendall also presented a computer learning environment for teaching optics and showed that while more time is required for the computer visualization than for traditional instruction, students had a positive experience and tended to be more actively engaged in the learning process (1995).

Teaching about the Human Eye

Whether and how to deal with the human eye when teaching optics is also well-documented in the literature, though few of such claims are substantiated by research. Jones asserts that we must be careful when deciding whether to use the human eye as a teaching tool in optics, because it may not aid understanding (Jones, 1976). Conversely, Ronen and Eylong argue that incorporating a functional model of the human eye throughout the learning process can lead to an increased understanding of optics principles (Ronen & Eylong, 1983).

Methods for teaching the human eye in the context of optics include the following: using the blind-spot of the human to learn about image formation (Farkas, Donnelly, Henriksen, & Ramsier, 2004), and utilizing pinholes and converging lenses successively to progress toward an understanding of the eye (Fred Goldberg, Bendall, & Galili, 1991). Specific suggestions for experiments also exist, for example from Edwards *et al.* (1975), in a three-part article by Mullin, (Mullin, 1966a, 1966b, 1966c), and by Arell and Kolari (Arell & Kolari, 1978), to name just a few. Many of the above claims have no published measures of success or hardships as determined by research, and as such they were not used to inform this study. While this work is recognized as existing in the literature, it should be noted that the creation of the learning materials from this work were based on the research collected as a part of this study.

2.8 Wavefront Aberrometry

Wavefront aberrometry is a relatively new method of diagnosing vision defects. Though at present it is used mainly during surgical corrective procedures (such as Laser-Assisted In-Situ Keratomileusis, or LASIK), it is gaining popularity quickly and could very potentially be used in determining standard corrective lens prescriptions. The process of wavefront aberrometry and the associated physics concepts are presented here.

2.8.1 History and Development of Wavefront Aberrometry

Hermann von Helmholtz was one of the first people to study the detailed structure of the human eye. In fact, he was the first to look at a living retina through the use of his Augenspiegel (known as the ophthalmoscope in English) in 1850 (Bennet & Rabbetts, 1989). A detailed description of the ophthalmoscope and other similar optical instruments can be found, for example, in Parel, Crock and Perićič (1980). However, Helmholtz was not the first to take an interest in vision and diagnosis of defects of the eye. An astronomer named Christopher Scheiner first demonstrated the possibility of measuring aberrations in the eye around 1600 (Thibos, 2000). He did so by placing an opaque flat disk with two pinholes, now known as a Scheiner disk, in front of the eye and focusing on a bright distant object, such as a star. The pinholes have to be small compared to the size of the pupil to let a small amount of light through; the star serves as a source for parallel light rays. Through his experiments, Scheiner showed that an eye that was either myopic or hyperopic (nearsighted or farsighted) would see a double image of the object, whereas a perfect eye would see a single image. By adding the appropriate corrective lenses in front of the eye, this double vision could easily be fixed. However, this system relied on the patient's interpretation of what he/she was seeing. Scheiner later proposed a more objective system in which the light was examined after it had bounced off the retina and exited the eye.

Around the turn of the twentieth century, M. Tscherning began investigating monochromatic aberrations in the optical system and designed an instrument, the "Aberroskop", to study these aberrations (Biedermann, 2002). The principle behind this instrument is still used in contemporary aberrometers, and will be discussed in the following section. At about the same time that Tscherning was working on monochromatic aberrations, J. Hartmann was developing a method for testing precision optics for telescopes. He proposed that if a perforated screen was placed at the exit pupil of the lens, the focal plane could quite accurately be described by measuring the location of the created bundles of rays. The light could then be measured with respect to the focal plane rather than the incidence of the beams; this procedure was not only objective, but far more accurate than previous ones as well. This method, known as the

Hartmann Test, was very popular in workshops and laboratories, though it was somewhat complicated (Biedermann, 2002). In 1971, Shack and Platt presented an adaptation of Hartmann's lens test in which the perforated screen was replaced with an array of small lenses. The merger of these two ideas formed one of the current aberrometry systems, the Hartmann-Shack aberrometer.

2.8.2 Physics of Wavefront Aberrometry

Principles of Aberrometry

Wavefront aberrometry can be described in two ways: through the use of ray optics or wave optics (Thibos, 2000). However, the target audience for this study knew only ray optics, and to varying degrees. While some parts of the aberrometer cannot be fully understood without considering the wave description of light, one can understand the basics of wavefront aberrometry by considering only ray optics.

The foundation of wavefront aberrometry is the principle of focal shift. If a lens is perfect, it will refract all incident beams of light through the focal point along a plane parallel to the optical axis. However, an aberrated lens refracts light either in front of or behind the focal point. This change in position of the light is known as the focal shift. Since the focal shift is dependent on the local aberrations in the lens, examinations of the focal shifts of many rays of light through a lens to find local aberrations can be combined to form a bigger picture of the aberrations in the lens as a whole (de Brabander, 2004).

There are four types of aberrometers: ray tracing, Hartmann-Shack, Tscherning, and automatic retinoscopy. Because of its popularity when diagnosing vision defects and for treatment using laser surgery procedures, this work will focus on the Hartmann-Shack aberrometer (Atchinson, 2005).

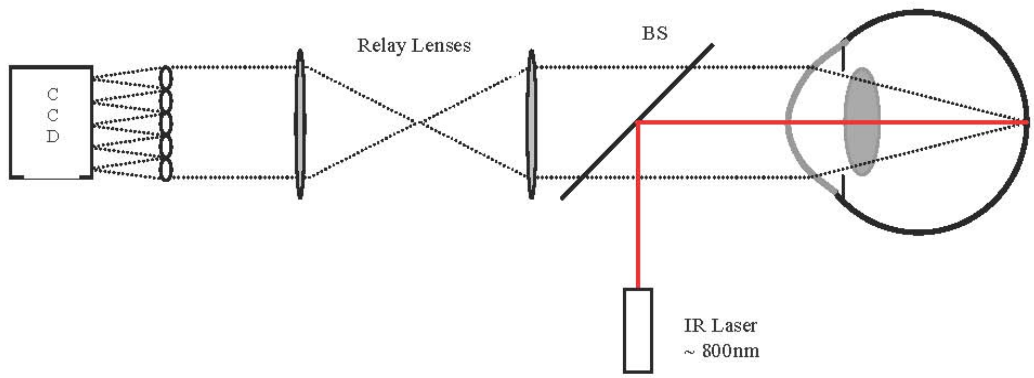
Four criteria are used to classify aberrometers: subjective/objective, serial/parallel, single-pass/double-pass, and forward/backward projection. The first classification is of considerable importance for reliability. Objective measurements are performed by the aberrometer independently, whereas subjective (or psychophysical) measurements require action by the patient. Not only are objective measurements faster, they also eliminate problems that might occur because of the communication abilities of the patient. The serial or parallel classification refers to how the data points are collected by the aberrometer. In serial collection, each point is measured individually, resulting in a longer measurement time. Parallel collection allows for a quicker measurement, but for severe aberrations can result in an effect known as crossover in which each data point is attributed to an incorrect part of the grid. Each time light passes through the eye, it is exposed to the aberrations of the system. The ideal system is therefore a single-pass, as it allows for the most straightforward analysis; however, objective systems require a double-pass of the light. The final classification, forward/backward projection, refers to how the measurement is recorded. In forward projection, the focal shifts are projected onto the retina and in a backward projection they are projected onto a screen or CCD camera (Rozema, Van Dyck, & Tassignon, 2005).

Hartmann-Shack Aberrometer

The Hartmann-Shack type of aberrometer is classified as an objective, double-pass, backward projection system. Whether data are collected serial or parallel is dependent upon the individual models of aberrometer. Two examples of popular aberrometers are the Zywave by Baush & Lomb and WASCA by Carl Zeiss Meditec. The entire test can be done in less than one second, and in fact on the order of 30ms. The measurement is taken as quickly as possible to minimize effects of the patient moving during the procedure.

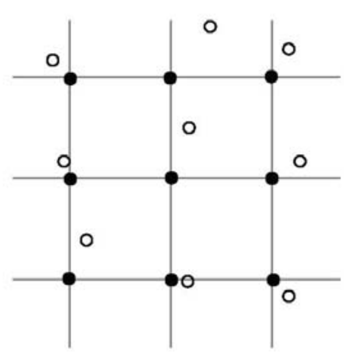
Figure 2.7 shows the simplified experimental set up for a Hartmann-Shack aberrometer. A low power infrared laser beam, approximately 800nm wavelength, is shone into the eye where it lands on the retina. This essentially creates a point source of light that then illuminates the eye from behind. The projection of this light out of the eye is the backward projection. As the light comes out of the eye, it picks up all of the aberrations from the ocular system. This light has therefore gone through the eye twice – once on the way into the eye, and then again on the way back out. This path technically makes the process a double-pass system. However, because of the properties of the light that are used to create the point source, this system achieves accuracy closer to that of a single-pass set up (Rozema, et al., 2005).

Figure 2.7 Experimental setup for Hartmann-Shack type aberrometer, adapted from (Rozema, et al., 2005)



After exiting the eye, the aberrated light passes through a set of relay lenses and is then projected onto an array of small lenses. These lenses, the contribution which Shack made to Hartmann's proposed system, then produce many spots of light which are focused onto a CCD camera. Depending on the model, there are between 100-1500 data samples possible. The focal shift of each spot is measured to obtain information about the aberrations present in the ocular system.

Figure 2.8 Example of a grid produced by the aberrometer, where solid dots are the reference points and the hollow dots are the measured values.



Data Analysis and Zernike Polynomials

In comparing the position of each spot of light to the known position for a perfect eye, two factors are considered important: the radial distance away, ρ, and the azimuthal angle, φ. This set of these measurements is then used as the data from which the aberrations are calculated. The aberrations are calculated using a mathematical function known as Zernike polynomials (Thibos, 2000). In effect, each polynomial corresponds to an aberration – higher order aberrations correspond to higher order polynomials. Because they are defined on a unit circle, use of Zernike polynomials to quantify defects of the eye requires that the pupil size be known as well. In most cases, the reference axis is along the line of sight of the patient. In general, the number of polynomials used corresponds to the spatial resolution of the wavefront image. Depending on the brand of aberrometer, the number of polynomials used ranges from 20, or 5$^{\text{th}}$ order, up to 65, or 10$^{\text{th}}$ order (Rozema, et al., 2005).

Zernike polynomials are a set of even and odd orthogonal functions defined on a sphere; they can be written in either terms of hypergeometric functions or the Jacobi polynomial, and are also related to Bessel functions. They are given as follows:

$$U_n^m(\rho,\phi) = R_n^m(\rho) \begin{matrix}\sin\\ \cos\end{matrix}(m\phi)$$

$$R_n^m(\rho) = \begin{cases} \displaystyle\sum_{l=0}^{\frac{n-m}{2}} \frac{(-1)^l (n-1)^l \rho^{n-2l}}{l!\left[\frac{1}{2}(n+m)-l\right]!\left[\frac{1}{2}(n-m)-l\right]!} & \text{if } (n-m) \text{ even} \\ 0 & \text{if } (n-m) \text{ odd} \end{cases}$$

The radial function could alternatively be expressed using the hypergeometric functions as

$$R_n^m(\rho) = \frac{\Gamma(n+1)\,{}_2F_1\left(-\frac{1}{2}(n-m), \frac{1}{2}(n+m); -n; \rho^{-2}\right)}{\Gamma\left(\frac{1}{2}(2+n-m)\right)\Gamma\left(\frac{1}{2}(2-n-m)\right)} \rho^n$$

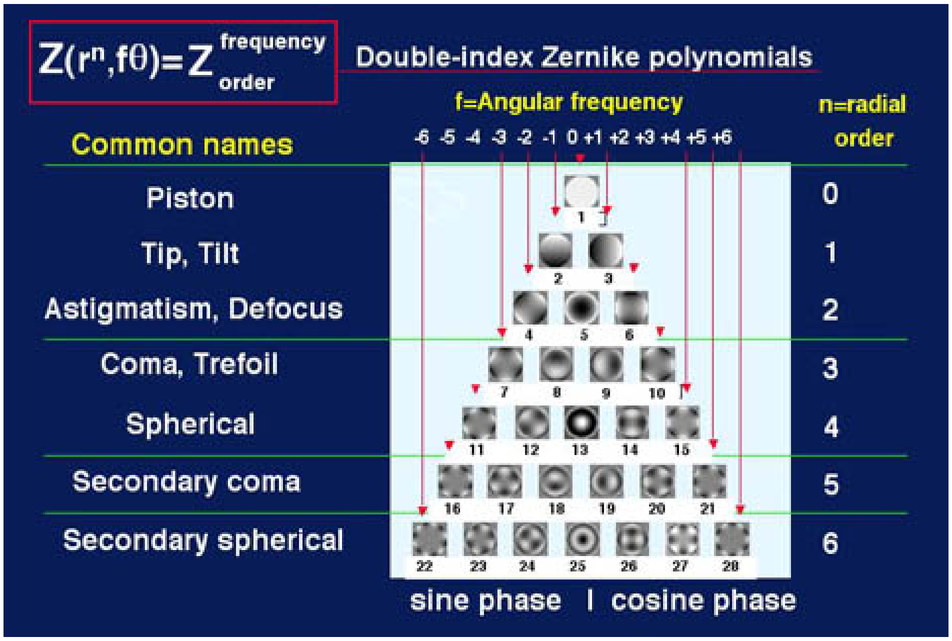
The first few non-zero radial components of the Zernike polynomials are expressed as

$$R_0^0(\rho) = 1$$
$$R_1^1(\rho) = \rho$$
$$R_2^0(\rho) = 2\rho^2 - 1$$
$$R_2^2(\rho) = \rho^2$$
$$R_3^1(\rho) = 3\rho^3 - 2\rho$$
$$R_3^3(\rho) = \rho^3$$
$$R_4^0(\rho) = 6\rho^4 - 6\rho^2 + 1$$
$$R_4^2(\rho) = 4\rho^4 - 3\rho^2$$
$$R_4^4(\rho) = \rho^4$$

The above properties and others including normalization, orthogonality conditions, generating functions, and recurrence relations can be found, for example, in Born and Wolf (1989).

The Zernike polynomials used to express the different aberrations of the eye involve three components: a normalization constant, the polynomial for the radial function, and the sinusoidal harmonic term. As such, each polynomial is represented as Z_n^f where n is the order of the polynomial and f is the frequency of the sinusoidal term.

Figure 2.9 Periodic table of aberrations, from Thibos (1999).



Thibos recommends thinking of these aberrations as having as being part of a period table of sorts. His illustration can be found in Figure 2.9, and displays both the order and frequency of a number of different aberrations. As can be seen in the picture, higher orders correspond to more complex aberrations, and frequency corresponds to the orientation. In terms of frequency, the negative and positive values refer to the function being a sine or cosine, respectively.

Table 2.1 Common aberrations in Zernike expression.

	m	n	Z	Expression
Defocus	2	0	Z_2^0	$\sqrt{2}\left(2r^2-1\right)$
Coma	3	1	Z_3^{-1}	$\sqrt{8}\left(3r^3-2r\right)\sin\left(\theta\right)$
Astigmatism	2	2	Z_2^{+2}	$\sqrt{6}r^2\cos\left(2\theta\right)$
Spherical Aberration	4	0	Z_4^0	$\sqrt{2}\left(6r^4-6r^2+1\right)$

In this notation, common aberrations can be written in the notation of Born and Wolf, and are seen in Table 2.1. To mathematically quantify the total aberrations of an individual eye, a weighted sum of these Zernike expressions is then determined (Thibos, Applegate, Schwiegerling, & Webb, 2000).

Clearly, it would not be reasonable to expect introductory-level students to construct an understanding of every aspect of wavefront aberrometry. As such, the aspects of aberrometry relevant to student understanding in this dissertation are: light creating a point source and moving forward through the eye, the set of lenses which create the Hartmanogram, or grid pattern, how nearsightedness/farsightedness and aberrations affect the grid pattern, a basic idea of how the grid pattern is interpreted, and the objective nature of this type of diagnosis.

2.9 Summary

This chapter reviewed research related to all aspects of this study including constructivism, transfer of learning, models of student reasoning, meaningful understanding, conceptual change, previous studies on student understanding of optics and related topics, and the physics of wavefront aberrometry.

From the constructivist theories, I adopt a mix of both Piagetian and Vygotskian perspectives. Specific emphasis comes from Piaget's notion of assimilation and accommodation being two types of knowledge construction as well as Vygotsky's emphasis on the social aspects of learning and the Zone of Proximal Development (Piaget, 1964; Vygotsky, 1978). In terms of Philips' dimensions of constructivism (Phillips, 1995), I take the perspective that meaning is created by the individual through active engagement with the environment, and that the constructed meaning is valid only within the individual and has no absolute correspondence to the outside world.

When examining transfer of learning, I approach the subject from a contemporary view in which the learner's perspective is emphasized. I view transfer as a dynamic, active process in which learners must create a knowledge structure in the new context instead of simply applying an existing knowledge structure. I also regard this knowledge creation as a complex process which is constantly moderated by controlling factors such as epistemic states, emotions, and motivation.

CHAPTER 3 - **Research Methodology**

3.1 Introduction

This chapter begins with a discussion of how vision diagnosis is taught in typical existing curricula and continues the research setting and the preliminary research plan. Methodological perspectives follow, and contain information on research perspectives and credibility and dependability of the study. Also presented are philosophical perspectives, including both epistemology and ontology. The final sections discuss the research tools and techniques used in this study.

3.2 Current Curriculum on Vision and Diagnosis

Introductory physics curriculum nearly always includes some information about light and basic ray optics. The concept of a wave front is also often discussed, though typically as a precursor to diffraction and interference. The degree to which the human eye is discussed seems to vary from text to text, as does that of vision diagnosis and corrective lenses.

A conceptual-based text by Hewitt (2006) discusses light and related phenomena in the second to last section of the book. Some of the included subjects are: the eye and how we see light, reflection, refraction, mirrors, lenses, chromatic and spherical aberrations in lenses, and wavefronts in terms of diffraction and interference. Giancoli's algebra-based text (2005) includes many of the same topics, most of which are located about two-thirds of the way through the book. The human eye is discussed in more detail, as are combinations of lenses and therefore vision correction. Four chapters of the calculus-based text by Halliday, Resnick and Walker are dedicated to light and related topics (2008). Most topics are presented with more mathematical rigor as expected, however considerably less about the human eye is discussed, and there is no mention of aberrations.

Because much of the foundational material is already presented in the typical introductory level course, the addition of wavefront aberrometry to the curriculum will provide the opportunity to combine the ideas of lenses, vision, diagnosis and correction and potentially to lead students to a more comprehensive understanding of the material. The learning materials on wavefront aberrometry could easily be placed immediately following a discussion of light and lenses, and can be done during a traditional lab or studio section.

3.3 Research Setting

This study was conducted at Kansas State University. Kansas State is a land-grant university in the American Midwest. Total enrollment of the university is approximately 23,000 including both undergraduates and graduates.

3.3.1 Ethical Considerations

Because this study involved the use of human subjects, ethical considerations were of utmost importance. The study was approved by the Kansas State University Institutional Review Board (IRB), and the researcher completed IRB training modules on human subject research. All participation was on a volunteer basis, and all participants were educated about the study so that they could provide informed consent using the IRB form found in Appendix A. Confidentiality was maintained by using pseudonyms to label data. The participants were also assured that their responses would in no way affect their academic work, and as such the students were guaranteed protection from harm.

3.3.2 Participant Demographics

The pilot study included research participants from several demographics. During Summer 2006, interviews were conducted with two different groups: graduate students in physics, and undergraduates participating in a summer research opportunity. Because of the nature of these groups, their backgrounds varied widely. The graduate students ranged from second to fifth year, and included both American and international students. The undergraduates were from institutions all over the country, and were mainly at the beginning of their third or fourth year of study in physics or a related field. During Fall 2006, a short qualitative survey was conducted with students in the second semester of an algebra-based introductory level physics course, *General Physics*. These students are enrolled in majors such as biology, animal science, and other life science disciplines – many are pre-medicine or pre-veterinary. *General Physics* students are enrolled in lecture, lab and recitation sections separately; the survey was given during lab.

All other participants in subsequent phases of the study were enrolled in *General Physics* or in *Engineering Physics*, a calculus-based introductory level course. Students in the *Engineering Physics* course come primarily from the College of Engineering, but also from science disciplines such as physics and chemistry. Because *Engineering Physics* students and

General Physics students have approximately the same likelihood of having taken a high school physics course, they have nearly the same prior-knowledge of optics if interviewed pre-instruction in their respective courses. For this reason, we had considerable flexibility in selecting which section to interview based on the number of volunteers.

3.3.3 Participant Selection

Volunteers were recruited in such a way that the highest possible number of students in each course was given the opportunity to participate. This typically involved the researcher making an announcement during lecture and allowing all those interested to fill out an availability form. This form requested only contact information and the student's availability. The announcement included information about the study, emphasis on the voluntary nature of participation, assurances that it would in no way affect their course grade, and information about a monetary compensation for their time. Volunteers were paid $10 per session, with each session lasting 60 minutes or less.

From the volunteers, final participants were chosen strictly based on availability. This method is called "convenience sampling" by Gay *et al.* (2006). It should be noted, however, that the participants were varied in their performance in the course, interest in course material, and background. Also, efforts were made to ensure that both genders were sufficiently represented in proportion to their numbers in the course.

3.4 Preliminary Research Plan

This research project consists of four distinct phases. The first phase served as a Pilot Study for the project. During this phase, students' understanding of the human eye was explored, along with how they built an understanding of wavefront aberrometry. The first part of the study – Phase 1a – consisted of semi-structured formal interviews with graduate and undergraduate students. To ascertain that the information obtained from the interviews was representative of the larger population, a short qualitative survey about the functions of the eye were also given to approximately 150 undergraduates in Phase 1b. The information obtained from this phase allowed for the design of subsequent phases. Phase 1c involved the first interviews focusing on topics of wavefront aberrometry.

Phase 2 allowed for a more concentrated look at how students understand wavefront aberrometry. Learning/teaching interviews were conducted with the introductory-level students;

the first interview provided information and activities relating to the human eye, while the second interview involved scaffolding activities in which students could construct an understanding of wavefront aberrometry. This setting allowed for the investigation of transfer of learning, as well as what resources were being activated by students. Interviews were conducted with individuals and also with small groups of approximately three students. This phase led to the development of an instructional module about wavefront aberrometry.

The third and fourth phases involved the pilot-testing and implementation of the instructional module using students who were post-instruction in light and optics from a traditional lecture course. A detailed description of the entire research process can be found in Chapter 4.

3.5 Methodological Perspectives

The entire research project was carried out using qualitative research methods. On page 14 of their text, Gay *et al.* describe qualitative researchers as those who "seek to probe deeply into the research setting to obtain in-depth understandings … conduct in-context research that allows them to uncover subtle, less overt, personal understandings" (Gay, et al., 2006). The richly detailed information about a phenomenon that results from qualitative research allows for meaningful conclusions.

Creswell presents five traditions of qualitative research: biography, case study, grounded theory, phenomenology, and ethnography (Creswell, 1998). Each of the different traditions serve a different purpose in qualitative research, and at times the traditions may be blended to obtain the best information about a phenomenon. For the purposes of this study, Creswell's grounded theory along with another approach known as phenomenography are used as a guiding framework are discussed in the following sections.

3.5.1 Phenomenology

Phenomenology is different from other theories in qualitative research in that it focuses on the subjective experiences of the participants. A phenomenological approach is one in which the researcher brackets all preconceived notions about the phenomenon, and in which the data are analyzed in such a way that the experiences of the participants are expressed (Patton, 1990).

3.5.2 Grounded Theory

This study used a grounded theory approach in order to elicit themes across students. Grounded Theory was developed by Glaser and Strauss to align with traditional methods of scientific research (1967). This alignment with scientific methods is achieved by assuring significance of results, compatibility between theory and observations, reproducibility of results, and other necessary qualities (Corbin & Strauss, 1990). In a true grounded theory, the research questions are only statements of what will be researched. Through data analysis, or coding, the researcher builds a theory that answers the research questions, and then assures the validity of the theory through the continual analysis of more data (Strauss & Corbin, 1990). As highlighted repeatedly by Charmaz, the most important part of a grounded theory analysis is to remain close to your data in order that the data itself guides the theory instead of any researcher bias (Charmaz, 2006). The grounded theory methodology was used primarily in the initial phases of the research project in order to obtain a theory of how students understand the physics of the human eye.

3.5.3 Phenomenography

To understand how individual students constructed an understanding of wavefront aberrometry, this research used a phenomenographic approach. On page 31 of his 1986 paper on phenomenography, Marton describes the method as being useful "for mapping the qualitatively different ways in which people experience, conceptualize, perceive, and understand various aspects of, and phenomena in, the world around them" (1986). Phenomenography highlights the different ways that people can understand a given situation. In terms of this study, it allows the many ways in which students can understand wavefront aberrometry to be drawn-out of the interviews. Knowledge of these possible paths to understanding can provide a guide for how instructional materials should be created such that the most accessible paths are taken to arrive at the 'correct' understanding of the phenomena. A phenomenographic approach was used in the later stages of this study in order to examine students' knowledge construction, and specifically to investigate the variations between students' models of understanding.

3.5.4 Data Collection

Consistent with the above methodologies, the data for this study were obtained via interviewing techniques. All interviews were video and audio recorded. Any sketches or other works created by the participants were kept, as well as field notes and observation notes as needed. Each interview was transcribed to create the primary data source. Two types of interviewing techniques were used throughout the project: clinical interviews, and learning/teaching interviews.

Clinical Interviews

The clinical interviews were used primarily in the initial stages of the project (Seidman, 1991). The questions were open-ended in nature, and included many question types such as descriptive (asking the student to describe what they see or think), opinion/value, and structural (how students organize knowledge). A protocol was created for each set of interviews, so the questions asked of each participant were the same. However, the interviews were semi-structured in nature, which allowed for variation from one participant to the next. This room for variation allowed the researcher to follow up with probing questions to pursue student ideas, while still asking the same questions of each participant.

Learning/Teaching Interviews

In nearly all stages of the project, learning/teaching interviews were used as the primary method of data collection, either with individuals or small groups of two to four students. The learning/teaching interview is a form of mock instruction which allows the researcher to focus on the dynamics of students' construction of knowledge (Englehardt & Corpuz, 2003). In a learning/teaching interview, the researcher is not a passive observer. On the contrary, the researcher plays the role of instructor or facilitator by engaging the students, asking follow-up and probing questions, and providing scaffolding as necessary. The rich context of the learning/teaching interview allows for the investigation of how students interact with scaffolding activities and how they transfer prior knowledge to construct an understanding of the phenomenon being studied.

3.5.5 Data Analysis

Because of the nature of qualitative research, an extensive body of data is obtained during the collection process. These data include the transcripts of each interview, as well as the sketches made by students during those interviews. To make this large body of data more approachable, it was analyzed using Colaizzi's seven steps of phenomenological analysis (Cohen & Manion, 1994). Those steps are:

1. Review collected data and become familiar with it, gaining insights into inherent meanings.
2. Extract significant statements from the data that are most central to the phenomenon being studied.
3. Formulate meaning from the significant statements.
4. Organize meanings into clusters of themes, which reveal trends and patterns in the data.
5. Create an 'exhaustive description' of participants' ideas and feelings on each theme.
6. Identify a fundamental structure in each exhaustive description.
7. Perform member checks by taking the formulated meanings back to the participant for verification.

This process involves the examination of each participant as an individual, as well as the identification of similarities and differences among participants. If any questions arise, the original transcript is consulted directly. It should be noted that this process aligns with what Marton describes as process for analyzing phenomenographic data: "quotes are sorted into piles, borderline cases are examined, and eventually the criterion attributes for each group are made explicit. In this way, the groups of quotes are arranged, rearranged, are narrowed into categories, and finally are defined in terms of core meanings …" (Marton, 1986). As is common in a grounded theory study, the data are coded multiple times and distilled repeatedly until a theory can be extracted (Glaser & Strauss, 1967).

3.5.6 Credibility

Unlike typical laboratory research where repeatability is a criterion for good data, qualitative research validity lies in its credibility. Credibility, sometimes also referred to as trustworthiness, involves the richness of the data and the accuracy with which it represents the multiple realities experienced by the participants (Patton, 1990). Conducting an identical study in education research is not feasible due to different students, demographics, geographic location, institutional characteristics, etc. As such, to assure credibility, Mertens (2005) proposes six strategies of triangulation in order to assure credibility:

1. Prolonged and substantial engagement – spending adequate length and quality of time with the participants to accurately represent their perspective
2. Persistent observation – repeated encounters with the participants
3. Peer debriefing – discussing the project with an unbiased peer in order to explore alternative possibilities
4. Negative case analysis – searching for contradictory cases and resolving the analysis conflict
5. Progressive subjectivity – continually scrutinizing and inspecting all assumptions and emergent themes from the research
6. Member checks – confirming with the participant that the researcher's interpretation is accurate

The design of this study limited the ability for prolonged engagement or persistent observation, due to the short span of each interview. However, both negative case analysis and progressive subjectivity were used repeatedly throughout the analysis process to ensure accurate data analysis methods. Member checking during the interviews and peer debriefing during the post-analysis stages were also utilized to build credibility in this study.

Member Checks

During member checks, the participant has the opportunity to verify that the researcher's interpretations are correct. In some cases, this can occur in the form of a summary at the end of the interview, or even by the researcher sending a written synopsis to the participant. In this study, member checks were done continuously throughout the interview process. If at any point the participant was not understood, he/she was asked to elaborate. Member checking questions are slightly different than probing questions in that the goal of a member check is to ensure the accuracy of the researcher's interpretation, while probing questions are frequently aimed at obtaining more or new information. Often times the researcher would summarize the participant's previous answers to check for correctness. Finally, before the end of the final interview, participants were asked to summarize what had been done and to reflect on the activities and discussion.

Peer Debriefing

In peer debriefing exercises, a researcher discusses raw data, analysis, findings, and possible conclusions with others. During this study this process occurred naturally between researcher and advisors as well as during group seminars of research peers. These situations could be either formal in a seminar or presentation, or informally during discussions with fellow researchers.

Finally, in another method of triangulation, excerpts of raw data were made available for peer analysis. This allowed for a more extensive reliability check, as well as creating yet another mechanism for peer debriefing. This type of inter-rater reliability study was formally conducted after each phase of the research process to ensure reliability trustworthiness of the data anaylsis.

3.6 Philosophical Perspectives

Cohen and Manion (1994) state that there are four sets of assumptions that a researcher must consider before examining and interpreting a phenomena such as this study. The four assumptions that must be considered are: ontology, epistemology, human nature, and methodology. Each of the assumptions is described as having two dimensions. Methodological assumptions were included in the previous section; the other three assumptions are presented below, along with the possible dimensions and those chosen for this study.

3.6.1 Ontological Assumptions

Ontological assumptions are those that deal directly with the nature of what is being studied. The two dimensions of ontology are nominalism and realism. Whereas a realist feels that all objects exist independent of whether someone knows about them or how they are named, nominalists believe that objects exist only in the consciousness of an individual, and that labels are just created in the mind (Cohen & Manion, 1994).

This research focuses on the individuals involved, and how they construct knowledge and interact with their environment. In this respect, the focus is on the consciousness of the individual. Therefore, this research will be operated under nominalist ontological assumptions.

3.6.2 Epistemological Assumptions

Epistemology deals with basis of knowledge and knowing, and has the dimensions of positivism and anti-positivism. On page 6 of their book, Cohen and Manion explain that "to view that knowledge is hard, objective and tangible will demand of researchers an observer roll, together with an allegiance to the methods of natural science; to see knowledge as personal, subjective, and unique, however, imposes on researchers an involvement with their subjects and a rejection of the ways of the natural scientist". The first stance being described is positivism, the second is anti-positivism.

During the data collection phases of this study, both clinical and learning/teaching interviews were used. Because of the interactive nature of both of these settings, the researcher's role was far beyond that of an observer. This aligns with the belief that students build knowledge in individual and unique ways, and suggests an anti-positivist epistemological assumption. However data analysis was carried out under more positivist assumptions in that the researcher remained objective and examined the data for tangible patterns.

The notion of using different epistemological assumptions for different phases of the research is not unlike behaviors exhibited by the participants and students. In fact, Hammer and Elby (2002) discuss the epistemologies of students as being rather fluid in nature, changing for different circumstances and environments. Unlike the traditional view that students have one "unitary ontology", Hammer and Elby present the idea of a "manifold ontology" includes the epistemological modes of 'knowledge as propagated stuff', 'knowledge as free creation', and 'knowledge as fabricated stuff'. By undertaking Hammer and Elby's view of a "manifold ontology", we can examine students' construction of knowledge from the standpoint of what epistemological mode they are operating under, and what contexts provide impetus for the change of modes.

3.6.3 Assumptions of Human Nature

As stated by Cohen and Manion, the most important aspect of the assumptions of human nature are those that deal with the relationship between humans and their environment. Volunteerism and determinism are the two dimensions of human nature assumptions. A determinist views human nature as being determined by the environment. A volunteerist views humans as having a "free will" which allows them to control their environment.

This research focuses on what prior information and experiences students bring into the learning process. Participants were purposefully exposed to different environments and contexts during the learning process, and therefore the environment affected the participants. As such, this research is operated primarily under deterministic assumptions of human nature because the students were provided with previously-selected environments and did not have the option of choosing which experience they would encounter.

3.7 Chapter Summary

This chapter outlined the research methodology that guided this study. In particular, the study was conducted primarily using the constructivist theoretical construct and with introductory-level students at Kansas State University. Phenomenology and phenomenography were blended with grounded theory to form the methodological approach for this study. Various reliability checks such as member-checking and peer-debriefing were used to ascertain the validity of the qualitative data analysis. Also, the four assumptions about society and research were explicated in this chapter in order to provide an overall sense of how the study was conducted.

CHAPTER 4 - **Description of Phases**

This chapter provides a detailed account of the various phases of the research, and how each phase contributed to the research as a whole. Included here are the descriptions of the protocols as well as the activities which were presented to the participants.

The project began with a pilot study (Phase 1) meant to test the feasibility of the project as a whole. The Pilot Study consisted of three parts – two sets of semi-structured interviews and a qualitative survey. Phase 2 involved individual interviews with students who had not had instruction in light or optics. Phase 3 extended the project to include pre-instruction students in both group and individual settings. Finally, Phase 4 describes an implementation of the resultant materials in a large lab setting. The protocols used in each study phase can be found in Appendix A.

4.1 Phase 1 – Pilot Study

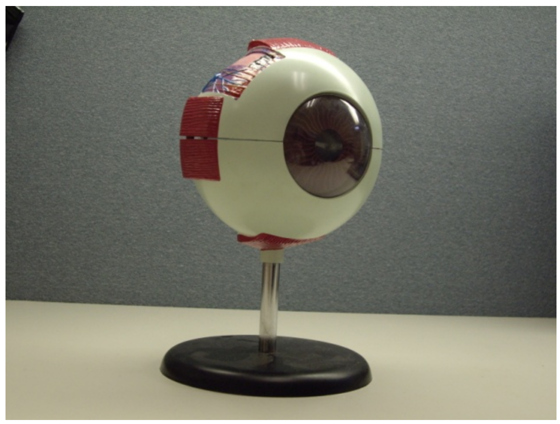
The pilot study for this project had three different components. The first component consisted of formal, semi-structured, clinical interviews that were conducted with a group of students to examine how much the students knew and understood about the human eye in general. In the second component, a short qualitative survey was conducted with a class similar to the study's target audience to examine the generalizability of the previous findings. Finally, the third component allowed for a pilot study of the wavefront aberrometry portion of this project. In the following sections of this chapter, each component of the pilot study will be described in detail.

4.1.1 Phase 1a – Pre-Instruction Individual Interviews

The first component of the pilot study was conducted during the Summer of 2006. A total of 13 students participated in this phase of the study, including 6 graduate students and 7 undergraduate students participating in a summer research opportunity. The students were not told of the content prior to the beginning of the interview, and therefore could not have done anything to prepare.

The goal of this component was to investigate how students perceive a series of models of the human eye. By having the students discuss the models, information about their knowledge of the human eye and its functions could be gained simultaneously. Initially, the participants could not see any of the models. Before the students were presented with any of the models, they were asked a series of questions about their experience with the field of optics, vision, and the human eye in general. Students were asked to explain how the eye worked. Afterwards, each model was presented one-at-a-time during the discussion, and all models remained visible after they were discussed. Students were asked to discuss each model in terms of how it related to their explanation of how the eye worked, and included discussion of features, functionality, and how well they liked each model.

Figure 4.1 Anatomically correct model

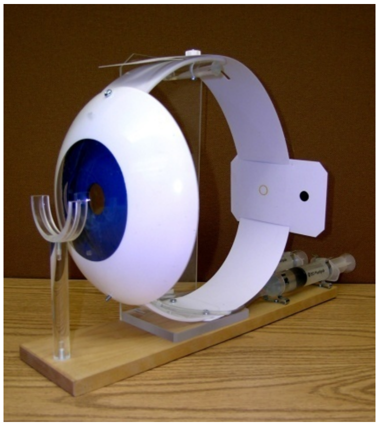


The first model presented was anatomically correct, but had no real functionality. This model can be seen in Figure 4.1. The second model was a CENCO brand bucket-style model of the eye, seen in Figure 4.2. The model has a fixed converging lens in the front, and a large opening so that water can be added. An adjustable metal screen serves as the retina for the model, and it is accompanied by a set of positive and negative lenses that can be used to illustrate vision correction. Models similar to this are frequently used in introductory college laboratories as well as in high schools.

Figure 4.2 CENCO bucket model

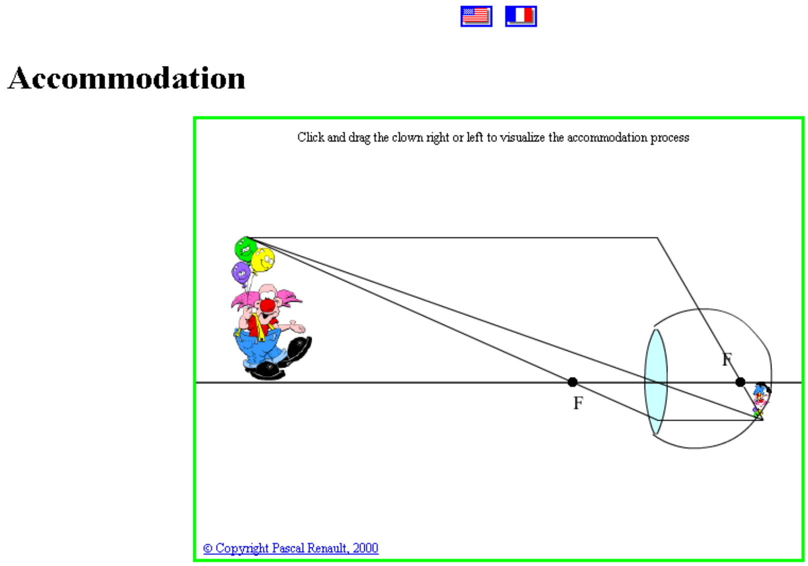
The third model can be seen in Figure 4.3. A similar model can be commercially obtained, for example, from American 3b Scientific. The functionality of this model includes the following: an adjustable size/shape to simulate vision defects, a set of lenses to illustrate vision correction, and a pliable lens connected to a set of syringes used to illustrate accommodation of the lens.

Figure 4.3 Eye model



The fourth and final model presented was an applet of the eye, found at http://mysite.verizon.net/vzeoacw1/eye_applet.html. A screen shot of the applet can be seen in Figure 4.4. By moving the position of the clown, one can watch both the image of the clown and the thickness of the eye lens change simultaneously.

Figure 4.4 Accommodation applet



The interviews concluded with students proposing their own model, and discussing which features they felt were important to include to create a best possible model to explain how the human eye works.

Click here to read Phase 1a Results.

4.1.2 Phase 1b – Qualitative Survey

The second component of the pilot study was completed during the Spring Semester of 2007. A short qualitative survey was administered to 155 students enrolled in an algebra-based introductory physics lab. The students were one week post-instruction on lenses and the human eye, and had completed a traditional lab using the CENCO type model as seen in Figure 4.2.

The goal of the qualitative survey was to test the generalizability of the findings from the pilot study to a larger audience similar to the project's target population. As such, the survey questions were based on the results of Phase 1a. The survey was intended to address two specific topics: if and how the eye lens changes and vision defects. The entire survey can be found in Appendix A.

The first two questions focus on whether the lens of the eye changes to see objects at varying distances, and if so, how. The third question out-right asked if the eye lens could change, and if so, how. The final question showed figures of normal, nearsighted, and farsighted eyes, and asked students to identify each defect and to state the kind of lens would be needed to correct such a defect.

Data were analyzed by following the phenomenographic approach as described in Chapter 3. Categories and themes were extracted from student responses.

Click here to read Phase 1b Results

4.1.3 Phase 1c – Pre-Instruction Aberrometry Interviews

The final component of the pilot study was conducted during the Spring semester of 2007. Learning/teaching interviews were conducted with twelve students enrolled in a calculus-based introductory-level physics course. The participants were pre-instruction in optics, but had learned about electromagnetic waves and light.

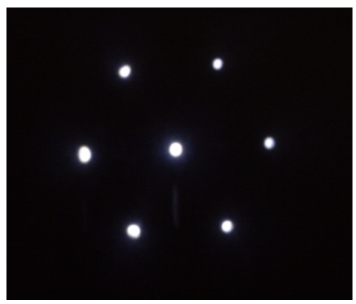
The goal of this component of the study was to look at how students build an understanding of wavefront aberrometry. The interviews were conducted under the assumption that students would have no prior knowledge about aberrometry, but that they would have some prior experience with optics. The protocol was therefore designed to follow how students develop a model of aberrometry.

Students were first given a copy of a typical eye chart, which was intended to frame the interview in the context of diagnosis. This introduction provided for discussion of how light travels and how we see in general. The model seen in Figure 4.3 was used for clarification, and often prompted further discussion. Of particular usefulness is that this model used has a pliable "lens" that is attached to a syringe system; by varying the amount of liquid in the lens, the radius of curvature of the lens changes and nicely models the accommodation process of the human eye.

Figure 4.5 Model of aberrometer

The final part of the interview involved the aberrometer. By adapting the method of modeling an aberrometer used by Colicchia and Wiesner (2006), the eye model discussed above could be used as the basis of a model aberrometer, as illustrated in Figure 4.5. In this adaptation, the eye model was used in combination with an array of small lenses, an LED light source, and a paper screen. The lens array was placed in front of the "pupil", and the LED flashlight was clipped to the retina and arranged such that light was directed out through the lens of the eye, through the lenses, and onto the screen. The result is a grid pattern of light, which is representative of the grid pattern obtained in the wavefront aberrometry diagnosis technique, as shown in Figure 4.6.

Figure 4.6 - Grid pattern created by model aberrometer



After the aberrometer was set up, participants were asked to describe what was being modeled and to explain the resulting grid pattern. This led to a discussion about how the grid pattern would change because of defects in the eye or because of vision defects. Students were asked to make predictions, and then allowed to test their predictions using the model and explain any discrepancies. The pliable nature of the lens allowed for aberrations to be created in the lens by simply pushing on it. An image of the grid pattern resulting from an "aberrated" lens can be seen in Figure 4.7. Finally, students were asked to describe how such a system could be used to diagnose vision defects, and to discuss any advantages and disadvantages as compared to more traditional diagnosis methods. The interview ended with students being allowed to ask questions about the eye, aberrometer, or even the interview process.

Figure 4.7 Aberrated grid pattern

Click here to read Phase 1c Results

4.2 Phase 2 – Two-part Interviews

In the second phase of this study, the focus was shifted more towards wavefront aberrometry than the function of the eye. In particular, the goal of this study was to follow student reasoning from ideas about basic optics and vision and how they translate into an understanding of wavefront aberrometry. Because the previous components suggested that students have a variable understanding of the ocular system, each student was asked to complete an introduction to lenses and the eye before continuing with a discussion of wavefront aberrometry.

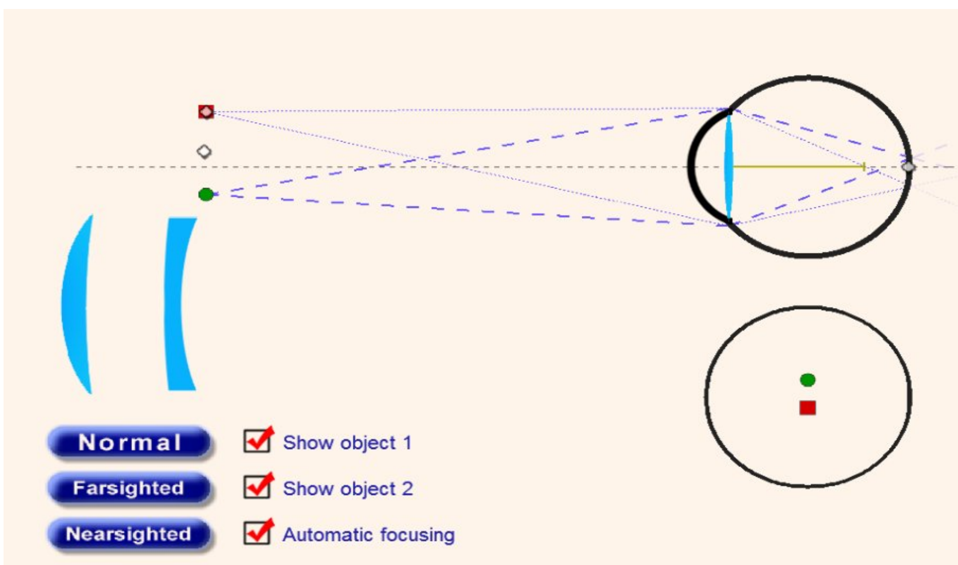
In this phase, two-part learning/teaching interviews were conducted with 18 students who were enrolled in the second semester of the calculus-based introductory-level physics course. All students were pre-instruction in light and lenses, but had covered the basic physics of waves during the previous semester.

4.2.1 First Interview – Eye and Lenses

The purpose of the first learning/teaching interview was to familiarize participants with the basics of lenses and the human eye. The key feature of this protocol is that the hands-on learning experiences are designed to follow a progressive development of a model of the eye through the activation and coordination of appropriate resources. It begins with the idea of a pinhole camera, adds a fixed lens, and finally adds an accommodating lens. The protocol is also constructed in a Learning Cycle format: the students are asked to first explore the phenomenon using the model and visualization, then the concepts are introduced in the text, and finally students are asked to apply the ideas by again using the model and visualization. Often, the application phase of one cycle simultaneously serves as the exploration for the next cycle. Along with the basic function of the eye, students work through information on vision defects such nearsightedness and farsightedness, as well as the corrections for those defects. The hands-on experience involved both the accommodating model of the eye (Figure 4.3) and a computer simulation, shown below.

Along with the functionality of vision defects and accommodation, the simulation had the added feature of visible ray diagrams. This allowed students to find the focal point – a clear image, as shown in the model – but also see what the focal point signified in terms of the light rays intersecting. It also allowed students to easily see if the focal point was in front of or behind the retina in the case of vision defects. The learning experience as a whole was designed to allow students to construct an understanding of simple lenses and optics of the human eye, which could then be later transferred to the context of wavefront aberrometry.

Figure 4.8 Computer simulation used during first interview



4.2.2 Second Interview - Aberrometry

Approximately one week after completion of the first interview, students participated in a second learning/teaching interview that focused on wavefront aberrometry. The protocol, which can be found in Appendix A, closely followed the protocol from previous aberrometry interviews to maintain comparable data. As in the pilot phase, the interview was framed in the context of diagnosis by first providing students with an eye chart. In this phase the opening questions about vision, defects and basics of lenses served as a review of topics which were discussed during the first meeting. In terms of aberrometry, the bulk of the interview still consisted of student predictions and explanations of how the grid pattern changed due to different vision defects and aberrations, as well as a discussion about how a tool such as aberrometry could be used to diagnose vision defects. The interview ended with a discussion of the advantages/disadvantages of the new method, and time for participants to ask any lingering questions about the process as a whole.

Click here to read Phase 2 Results

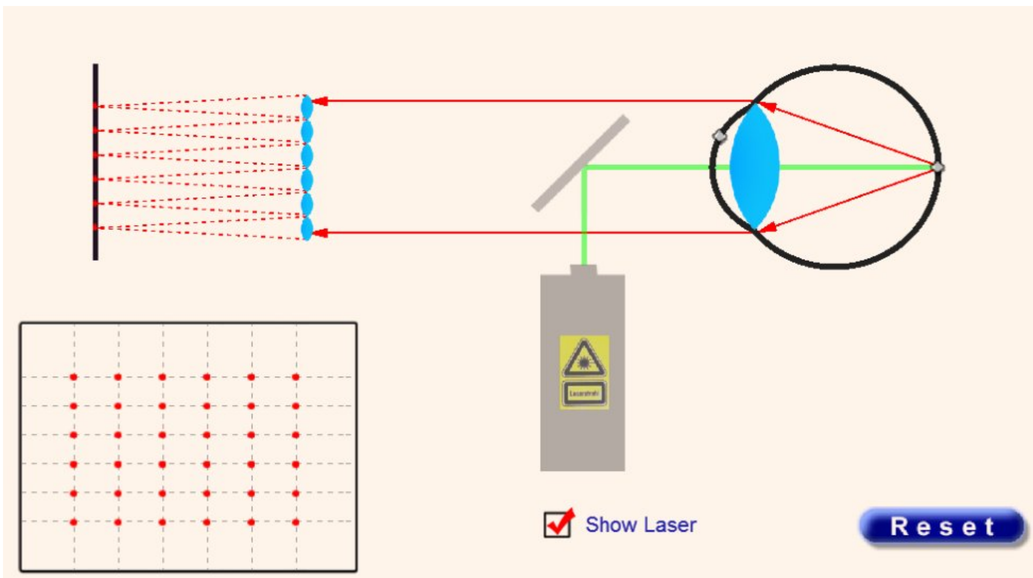
4.3 Phase 3 – Post-Instruction Interviews

The third part of this study continued to build upon prior phases focusing on wavefront aberrometry in two ways: first by extending the learning/teaching interviews to a group setting, and second, to examine whether students could complete the aberrometry protocol after traditional instruction in basic light and geometric optics. The goal of this study was to again follow student reasoning from ideas about basic optics and vision and how those ideas transfer into an understanding of wavefront aberrometry. Also, this phase was different in that all of the participants were post-instruction in light and basic geometric optics from a traditional lecture course in algebra-based introductory physics. The implicit assumption is that the students would learn the same basic concepts in the traditional instructional setting as if they had utilized the learning cycle materials on the human eye; however nothing is assumed about the students' ability to transfer their knowledge to the wavefront aberrometry context.

4.3.1 Phase 3a - Post-Instruction Group Interviews

In this phase, five groups with a total of 13 students were interviewed. All students had completed a traditional instructional unit on light and basic geometric optics including lectures, homework, lab activities, and an exam. Because the students were post-instruction, only one interview focusing on wavefront aberrometry was needed. The protocol used in this phase was nearly identical to one used in Phase 2, and can be found in Appendix A. The first difference was the addition of questions intended to find out what the students knew about the function of the eye and how they related to the model being used for the interview. Again, the interview was framed in the context of diagnosis by first providing students with an eye chart. The other addition is the use of a computer simulation of wavefront aberrometry. After completing the discussion about wavefront aberrometry, students were asked to work with the simulation and compare it to the hands-on model. They were also asked for the opinions about the simulation and hands-on model, and to identify any strengths or weaknesses of each representation. A screen shot of the simulation can be seen in Figure 4.9. As before, the interview ended with a discussion of the advantages and disadvantages of the new method and time for participants to ask any lingering questions about the process as a whole.

Figure 4.9 Computer simulation of wavefront aberrometry



4.3.2 Phase 3b - Post-Instruction Individual Worksheets

To move toward a more realistic instructional setting than the learning/teaching interview, the aberrometry interview protocol was translated into the form of a student worksheet. The participants in this portion of the study were also post-instruction in light and basic geometric optics from a traditional algebra-based introductory physics course. The participants completed the worksheet, which can be found in Appendix A, on an individual basis using the same eye model, aberrometry set-up and computer simulation as previous phases. Not only did this phase allow us to move toward a more realistic setting, but also allowed for the inclusion of a larger number of participants than would be possible with interviews. In all, 27 students participated in this phase of the study.

[Click here to read Phase 3 Results]

4.4 Phase 4 – Implementation

The fourth and final phase of this study was the implementation of the learning materials into a traditional lab setting. The implementation took place during the Fall semester of 2008 in the second semester of the algebra-based introductory physics course. The worksheets that served as the lab activity can be found in Appendix A. The actual implementation occurred during the lab component and involved approximately 200 students in six separate lab sections. As incentive for thoroughly completing the labs, the students were informed that 3-5 questions on their exam would directly cover the lab material.

In order to test the usability of the learning materials as designed, the researcher was not present during the lab sections. Instead the teaching assistants were given a short description of the lab activities and expected learning outcomes at their weekly set-up meeting, and allowed to run their lab section as usual. After the students had completed the lab activities and worksheets, they were returned to the researcher so that they could be photocopied, graded, and returned to the students for use as study material.

A post-activity assessment was not possible because this activity was completed within the traditional laboratory classroom. As such, student learning gains could not be measured; instead, student responses were analyzed using the same analysis methods utilized during the previous phases of the study.

Click here to read Phase 4 Results

4.5 Chapter 4 Conclusions

This chapter provided an overview of each of the different phases of the project, including rationalization for each phase as well as a complete description of the activities and participants. Phase 1 was a Pilot study focusing on the human eye, as well as the beginnings of wavefront aberrometry. In Phase 2, the learning/teaching interviews were more in-depth, and involved pre-instruction students. Post-instruction groups and individuals were included in Phase 3. In the final phase, the learning materials were implemented in a traditional laboratory setting.

Click here to continue to Chapter5 or jump to Chapter 6

CHAPTER 5 - **Resource Analysis**

Presented in this chapter are results from the resource analysis that was conducted on data from all phases of the study, including supporting excerpts from student statements. As described in section 3.5, the data were analyzed using grounded theory and phenomenographic approaches to examine the variations in student ideas and to detect possible themes. In general, student responses were coded to identify the resources that they were using when constructing their understanding, and to examine how they were activating and associating the resources while constructing an understanding of wavefront aberrometry. Also of particular interest is the context surrounding the use of each resource (Hammer, 2000).

Similar themes emerged across all phases of the study; those common threads are highlighted in this chapter. In particular some common themes include student ideas about the shape of the eye and how it affects the created image as well as how lenses interact with light.

Naturally, each phase of the study was slightly different from the others because of the natural progression of any research project. As such, also presented are interesting results based on the nuances of each phase. This chapter progresses chronologically with the study so that these variations are visible over time. For example, because the first group of interviews was conducted solely on the function of the human eye and models of it, the data obtained were different than in later phases of the project. Other differences include pre- versus post-instruction, individuals versus groups, and verbal versus written responses. Interesting emergent themes from each of these cases are presented when available.

5.1 Phase 1 – Pilot Study Results

The purpose of the Pilot Study was to test the feasibility of the research concept, and the results of the pilot study had a large impact on the progression of the entire study. It was found that students had varying degrees of knowledge about the human eye and vision, and many in fact knew very little about vision in general. Because of this variance and lack of knowledge, discussing the more advanced concept of wavefront aberrometry was unachievable. This realization guided the rest of the project in that all students who were interviewed after the pilot study had a concept introduction of some sort on the topics of basic optics and the human eye before the discussion moved to wavefront aberrometry. The following sections contain more details of the results of the pilot study.

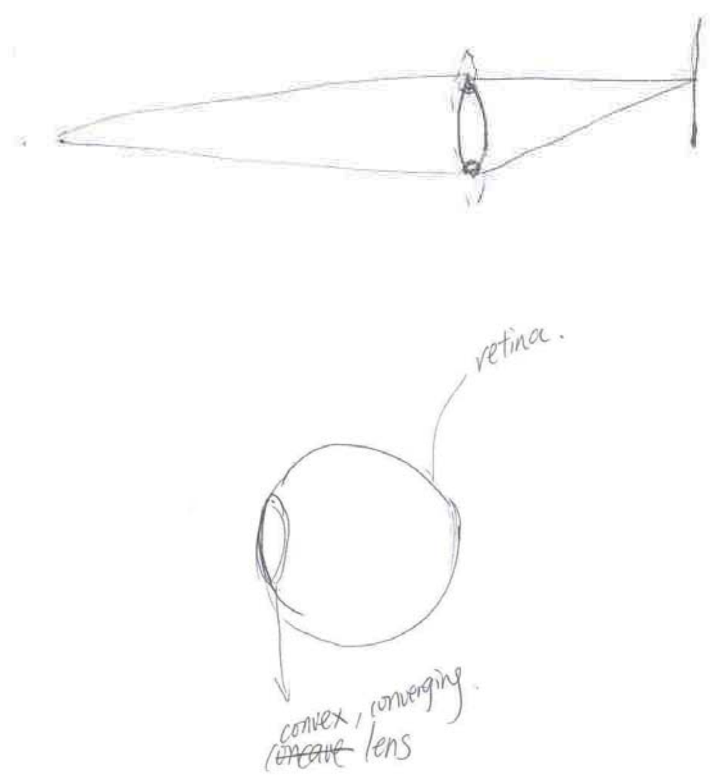
Click here to read Phase 1a Description

5.1.1 Phase 1a Results

The goal for Phase 1a was to investigate what students knew about the human eye and vision. Interview data were analyzed in terms of how students perceived a series of eye models and their knowledge of the human eye.

During the first portion of the interview, students were asked to describe how the human eye worked. One major trend in the data is that students describe the eye as being a two-part system, comprised of a lens and a screen (the retina). This is evident not only in their verbal responses, but also in the sketches that they draw. For example, see Figure 5.1. Very few students initially mentioned other parts such as the iris, cornea, etc.

Figure 5.1 Student sketches of light entering the eye



When asked about vision defects, less than half of the participants could explain near- and farsightedness. Of those who could accurately describe the defects, the vast majority indicated that they had corrective lenses for a vision defect. Most of the students felt that the problems resulted from a defect in the lens of the eye, and made no mention of the shape of the eye. In general, knowledge of the human eye varied widely among students, and did not seem to depend on their level of schooling.

Participant reactions to the models were also consistent across all levels of students. (Images of all models can be found in section 4.1.1.) In general, most participants realized the lack of functionality in the anatomical model; however, they liked this model because of its accurate representation of the form of an eye. The CENCO model generated comments about the "out-of-date" appearance. Students were concerned about the fact that it didn't look like an eye, and often times they did not understand the benefit of being able to fill the model with water. The white plastic eye model, on the other hand, was very well-liked because of its newer appearance and features. Only a couple of the students recognized that their lens was able to change shape as illustrated by the model. Some questioned the need for the out-of-round adjustment, which highlights the fact that they did not understand that nature of vision defects. Finally, the participants reacted well to the accommodation applet. They commented on being able to see all of the effects at once; however from the point of view of the observer, it was obvious that some of them overlooked things that were happening.

To follow-up on this component of the study, an additional five clinical interviews were conducted with upper-level undergraduate students, following the same protocol. However, these participants had just learned about the human eye in an upper-level optics course. As such, they were not representative of the target audience, and their responses were not included in the above data. At this point an additional qualitative survey was added to ascertain that the results of the first study were representative of the target audience.

Click here to read Phase 1b Description

5.1.2 Phase 1b Results

The results of the qualitative survey are summarized in Table 5.1, along with the question being answered in each case. The questions used on the qualitative survey were written to address specific themes from Phase 1a. Though the first two questions on the survey were technically different in that one asked about object moving away from the observer and the other asked about objects moving closer to the observer, all students answered in the same way for both questions, and therefore the responses listed are characteristic of both questions.

Table 5.1 Summary of results from qualitative survey

Q1/Q2 – Does the lens of the eye change to view objects at different distances?	
Lens of the eye changes	60%
Lens of the eye does not change	13.5%
Other things in the eye change (focal point, iris, etc)	20%
Lens of the eye moves	6.5%
Q3 – Can the lens of the eye change shape? How?	
Yes it can	65.8%
Muscles make it change	21.9%
No it cannot change	27.7%
Q4 – What is needed to correct for defective lenses?	
Converging or Diverging Lens is needed	75.5%
Focal point needs to change	11.6%

As shown in the table, 60% of students responded that the lens of the eye *does* change to see the varying distances of objects. Another 20% indicated that something in the eye had to change, for example the pupil or iris changes. Only one student indicated that it was impossible for the lens to change, but 13.5% said that it does not change in the given circumstance. Also interesting is the 6.5% of students who indicated that the lens of the eye actually moved, either forward or backward inside of the eye.

Question three directly asked "Can the lens in the eye change its shape? If yes, explain how these changes occur. If no, explain why it is not necessary." Only 27.7% of students said that it could not change shape – none of them explained why it was not necessary. A total of 65.8% of students indicated that the lens of the eye could change shape. This includes the 21.9% who indicated that the change occurred because of muscles. There were 20% of students who answered in the affirmative, but with no explanation of how.

Finally, question four dealt with vision defects of the eye. A fairly large 75.5% of students knew that a converging or diverging lens was required to correct the vision, and another 11.6% knew that the focal point had to move to correct the defect. It should be noted, however, that the above statistics do not account for whether the students assigned the converging/diverging lens to the appropriate defect.

Though the results of this qualitative survey do not exactly mimic the trends from the interviews in Phase 1a, one important result is clear: students have a wide range of knowledge about the human eye, its functions, and vision defects. In many respects, students who had traditional instruction on the eye and lenses had a more predictable, though not flawless, understanding of the eye. Though this study does confirm the basic knowledge of post-instruction students, no other particularly remarkable results were found.

Click here to read Phase 1c Description

5.1.3 Phase 1c Results

In this phase, the discussion centered on what students knew about the human eye and vision and also included in the protocol was a large component dealing with wavefront aberrometry. The following subsections present the themes that emerged from the discussion about the eye and vision as well as the themes that emerged during the discussion of the aberrometer.

Resources on Basic Principles of Light and Lenses

Because the students who participated in this portion of the study were pre-instruction in light and basic optics, the resources that they activate in these areas are of particular interest. The following are resources found to be prevalent in this group. Note that in this set of interviews, students were not directly asked about the shape of the eye so no data on that topic could be collected.

Light Moves as a Straight Line

The first resource, *light can be represented by a line*, was extracted partially from statements from participants, but mostly from their sketches. Of the 12 participants, nine made sketches of ray diagrams and each clearly represented light as a straight line coming from a source, though students were never directly asked about the form of light. This resource, in reality, may be less than helpful or even hinder their understanding. When standing alone, the resource that *light can be represented by a straight line* is not at all inappropriate. However, if the students believe that light can *only* travel as a straight line, this could deter them from understanding that altered wavefronts are a result of aberrations.

Shape of Lens and Image Focus

Seven of the 12 participants indicated that the shape of a lens changed how/where the image was focused. For example, the following conversation is from the discussion about the model's accommodating lens:

> Student: "When I push this one [the syringe], it changes the focus of the light."
>
> Interviewer: "Okay, how is it doing that?"
>
> Student: "By, uh, changing the shape of the lens."

Another student explained the accommodating lens of the model in the following way:

> "Well, this [pulling/pushing on syringes] changes the pressure – the amount of fluid in here [the lens] – which would change the diameter of the lens, which would determined how focused something would be. Or, like that's how you focus [the lens]."

Again, this resource which is a part of basic geometric optics is useful for students in understanding that an image focuses and that the location of the focal point depends on the shape of the lens.

The Human Eye

All participants were able to transfer at least some prior knowledge about how the eye works. Some examples include the naming of parts (i.e. retina, cornea, and iris) and many also knew that the image produced on the retina is upside down and must be "flipped" by the brain. However, in terms of the actual functioning of the eye, students had relatively little prior knowledge. Because of this lack of resources, it was quite difficult to get the students to talk about how the eye worked and even more difficult with the aberrometer.

Lenses Dividing up the Light

As discussed above, students had little prior knowledge about light and lenses. Naturally, this made the activation and association of resources difficult to identify – students simply did not have many resources in their toolbox. In fact, most transfer occurred in the understanding of the two-lens system created by the eye lens and the lenses in the array. As one student put it,

> "the [eye] lens focuses light onto the area of the array, and then the [array] lenses are breaking up light … and focusing it to their own point."

Students also seemed to believe that there was an "ideal" grid, though different ideas existed about what that ideal might be; some indicated symmetry while others thought that a specified intensity or the size of the dots should be known. This ideal reading concept is perhaps transferred from our typical notion of ideal vision, e.g. 20/20.

Light through Lenses

The data indicate that students do have many resources that are useful for understanding wavefront aberrometry. Perhaps most notable is the resource that *light entering a lens differently will focus differently*, as it is an idea central to wavefront aberrometry. This resource may in fact be based on a more basic p-prim that *changing inputs causes a change in outputs*, which can also be considered a basic cause-and-effect principle. When activated appropriately, this resource can be the key to understanding the concept. This resource was activated by 10 of the 12 participants. For example, one student used the resource to explain the deformed grid pattern in the following way:

> "[because of the aberration] light wouldn't shine through the lens as clearly. It would be reflected in all different directions … so now that you have a bending of the light, the focus [of the grid pattern] is just kind of messed up."

In this case, the student used the given resource to connect the ideas of light moving through an aberration with the visible effect of the deformed grid pattern. Notice, however, that the student incorrectly uses the term 'reflected' to describe the bending of light. This error was found in many of the transcripts from every phase of the study. The students frequently say the word 'reflection' when describing the bending of light, with some students even using 'diffraction' or other terms. Upon further exploration, however, we found that the issue is one of terminology and not understanding.

Subjectivity/Objectivity

The issue of subjectivity in measurement is one that was purposefully raised during discussion of both detection instruments. Most students (8 of 12) did not initially realize that any subjectivity was involved during diagnosis with an eye chart. In fact, five participants clearly stated that the eye chart was an objective diagnosis tool because it was exactly the same for every patient. This result indicates that the students' view of objectivity may have only a component of fairness and not include the patients' subjective interpretations. In any case where the issue of objectivity was not directly addressed by the student, they were prompted with questions such as "Did you ever try to guess at a letter you couldn't really see?" or "Did you ever have trouble telling the doctor how much clearer one line was than the next?" This scaffolding was in all cases adequate to get participants thinking along the lines of subjectivity. Interestingly, one student justified this type of guessing and subjectivity with the assertion that all people probably guess, so the results average out over the whole population. It should also be noted that no differences were detected between students who had glasses or contact lenses and those who did not. After discussing aberrometry, students were asked what the advantages and disadvantages of that type of system could be. The issue of subjectivity was raised by nine of 12 students, who stated that the eye chart was more subjective than the aberrometer. Based on these responses, the idea of objectivity now included a component of "not open to human interpretation" for many of the participants.

5.1.4 Phase 1 – Pilot Study Summary

The results of the initial pilot study indicated first and foremost that students have an inconsistent and incomplete understanding of how the human eye functions. Students were often unable to apply their model of the human eye to understand the physics of vision, and student knowledge of vision defects was limited. The large qualitative survey issued as the second part of the pilot study affirmed that even after minimal instruction in basic optics, students had a more coherent, correct, and consistent understanding of how the ocular system functioned at a basic level.

Finally, the third part of the pilot study indicates that some concept introduction about basic optics and the human eye is necessary to obtain rich, useful data about how students understand wavefront aberrometry. Students have a significant body of resources that they use to understand aberrometry – some appropriately and some inappropriately. The results also indicate that while most students have a large body of prior knowledge about the human eye and basic optics, much scaffolding will be needed to facilitate the application of that knowledge to wavefront aberrometry techniques.

Click here to read Phase 2 Description

5.2 Phase 2 Results

During the second phase of the project, the students participated in two interviews: a concept introduction about basic optics and the functions of the human eye, and a discussion centered on wavefront aberrometry. Illustrated again during the first interview was the wide variety of prior knowledge about the eye and vision that students have. Some of the students struggled to make it through the material, others expressed that it was all familiar to them. Regardless, the goal of the concept introduction was to provide students with a set of similar experiences and knowledge to enable a productive discussion of wavefront aberrometry during the second interview.

The first interview was utilized as a set up learning materials which provided students with a set of resources that could be useful for understanding wavefront aberrometry. As such, all data presented in this analysis were obtained from the second, teaching/learning interview, as that is where the context of wavefront aberrometry entered the discussion and is the true focus of this study. Presented here are both the similar themes from previous phases as well as those unique to this phase. Inter-rater reliability studies on the coding obtained 81% agreement before any discussion; all discrepancies were resolved in a short discussion.

5.2.1 Shape of the Eye and Image Focus

The students often used the resource that *the shape of the eye determines how well you can see,* and continue using such a resource to say that *if the shape changes, the focus change*. In the first interview, scaffolding was provided to the students which encouraged them to use both the model and the computer simulation to learn how adjusting the distance from the retina to the lens, thereby changing the shape of the eye. In particular, students were asked to discuss image quality and where the focal point was located with respect to the retina as they changed the length of the eye. Nearsightedness and farsightedness were explored in this manner. Therefore, the experiences provided during the first interview allowed the students to establish that the length of the eye – and therefore the distance from the retina to the lens – is a factor in how far away an object can be from the eye and still be in focus. Consider the following excerpt:

> Interviewer: "What do you think will happen to our grid pattern if the shape of the eye was not perfect?"
>
> Student: "You're looking at changing the distance, as far as the back of the eye … it just goes hand-in-hand with the length of your eye. So if you move it [the retina] back, you're going to have to move this [the screen] either backward or forward, I just don't remember which."

This resource was then activated to create the idea that *different eye shapes will make the grid focus at different distances.* In total, 12 of the 18 participants accurately predicted that this change of focus would occur when the shape of the eye was changed; they were able to test their predictions to see that the change did indeed occur. Though the remaining six students did not correctly predict the occurrence, they did observe and comment on it during the prediction-testing stage.

To an expert, the above resource may sound more fundamental that described. Because the different shapes of the eye are in essence a variation of the distance between the 'lens' and 'screen' (retina), it could appear that the resource is actually dealing with the eye as an optical system. However, there is no way of knowing the students are approaching the resource in this manner. In fact, many students used phrases which would indicate that they did not see this connection, such as saying that "long eyes make small grid patterns."

5.2.2 Shape of the Eye and Image Size

Students frequently use the smaller-grain resources known as phenomenological primitive (p-prim) when constructing understanding in new contexts (diSessa & Sherin, 1998). The following is one example.

> Interviewer: "What do you think will happen to our grid pattern if the shape of the eye was not perfect?"
>
> Student: "It [retina] is further away, so it [focal point] has to be closer to here, so these [dots of grid pattern] are going to be

smaller but brighter points, and when it [retina] is up here, they [dots of grid pattern] are going to be bigger fuzzier points."

In this case, the p-prim being used is that *closer objects appear larger*. This resource could have been activated from our everyday experiences, as things that are farther away from us appear to be smaller. However, this also could be seen with both the model and the simulation. As the object distance was increased, the changing image size was clearly visible. The transfer here is that *different shapes of the eye will make the grid pattern appear larger or smaller.* Half of the students (9 of 18) predicted that the size of the grid would change because of a differently-shaped eye.

The above resource can actually be viewed as a misapplication of a p-prim. In reality, the *closer is bigger* p-prim is one that deals with perception – we perceive objects that are closer to us as being larger. However, as used above this resource exists within the context of optics because of the lens in the eye. Within the context of optics, a more appropriate resource might be that *objects closer to a lens have larger images.* However, the interview data suggests that students are not using this resource and instead relying on the perception-based p-prim.

5.2.3 Lenses dividing up the light

Many students predicted that only the portion of the grid pattern corresponding to the location of the vision defect would be altered. One student's prediction is as follows:

> Interviewer: "What do you think will happen to our grid pattern if the lens of the eye has an aberration – a defect?
>
> Student: "The grid will change."
>
> Interviewer: "Okay – how do you think it might change?"
>
> Student: "I believe that for most of the eye, it would still be like this [normal grid pattern], but some areas would have – you know, they'd be imperfect."

This student and many others used the resource that *lenses only focus the light that enters them* when they predicted that only a portion of the grid would change. Using this reasoning, the altered light from the defect only entered some of the lenses, so the others would not produce a distorted image. The activation of this resource enabled students to construct the idea that: *A defect in the eye will only distort the part of the grid that is getting the light from the defect.*

From a general perspective, this notion may come from our everyday experiences; we cannot see things that are outside of our range of vision. However, it may also be linked to other ideas that have been presented in the literature about how students understand lenses. An example could be the commonly held idea that when half of a lens is covered, half of the image will disappear (Goldberg & McDermott, 1987). Consistent with this idea, the student might believe that light from that half of the object can no longer enter the lens, and as such will not contribute to the produced image.

The previous excerpt was taken from the prediction phase. In fact, 8 of 18 students made similar predictions. During the testing stage, the participants noted that more of the grid pattern changed than they had originally predicted. This was frequently explained by noting that a bigger aberration created a bigger distortion:

> "Well, the harder you push [on the lens] the more deformed the shape of these small dots [of grid pattern] – they go from circular to almost a dash shape. If you push hard enough, then eventually everything starts to get displaced."

This was also noted with other participants in previous phases of the project. The explanation that more deformation of a lens results in more distortion of the image could be the result of another resource, the p-prim *more cause results in more effect*.

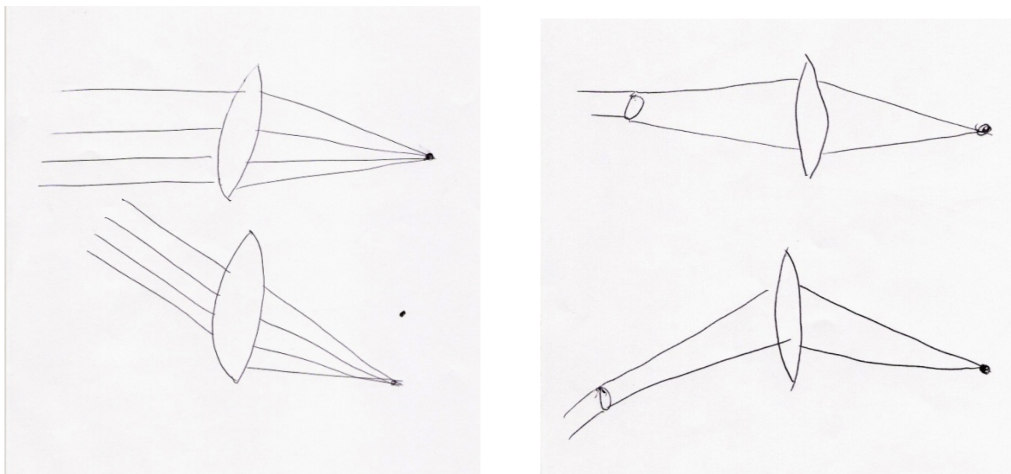
5.2.4 Light through lenses

Throughout the protocol, students were asked to predict and explain the changes to the grid pattern as a result of a defect in the lens. This in many cases led to a discussion of the way that light moves through a lens. In fact, in 17 of the 18 interviews this discussion occurred, making it the most widely-used resource throughout the phase. Consider the following excerpt from one of the interviews:

> Interviewer: "Why do you think that the grid pattern will change?"
>
> Student: "If you have a defect [in the lens], it's going to change the way that the light comes out of it, so it would have an effect on these lenses [of array] and how it comes out of them."

In this circumstance, the student is clearly using the resource that *light that enters a lens differently will focus differently*. This same resource was also prominent in previous phases as students attempted to explain the changes that occurred in the grid pattern. To more deeply probe this resource during this phase, students were asked to draw to sketches of light through a convex lens. In the first sketch, the light rays entered the lens parallel to the optical axis. In the second sketch, however, light rays were coming into the lens at an angle to the optical axis. All of the students recognized that the first case would produce a focal point at some location on the optical axis. The second task, however, produced two distinctly different answers. One example drawing from each case can be seen in Figure 5.2.

Figure 5.2 Two ideas about how light could focus through a lens



None of the students indicated, either in words or through their sketches, that the focal point would be at the exact same point. The idea of changing the way light enters a lens was not directly addressed during the provided experiences about the human eye and lenses; however, this resource and a very high frequency of use. This seems to suggest that this idea is in fact part of the more general phenomenological primitive (or p-prim) (diSessa & Sherin, 1998) that *a change in part A results in a change in part B,* or more simply stated, *propagation of changes.*

This notion was then transferred to the context of wavefront aberrometry in the following way: *because light from the aberrated lens is different, the grid pattern will change*. Ten of the 18 participants predicted that the position of the dots would change. Being able to activate this resource appropriately is essential for building an understanding of how the aberrometer works. One student, for example, used this resource when explaining how the aberrometer could be used to diagnose vision:

> "Well, then whatever light comes onto that grid … they could probably tell like if your eye was really defective – like maybe whether one side was more smashed in than the other side. Because what we did earlier was with the light coming back to [the grid] as different shaped in some points."

Another explained that:

> "So maybe it [the aberrometer] has a reading of what is normal. It can tell you whether there's a defect in the lens itself, if the dots are in a goofy pattern, like with the actual lens if it is messed up. It's not only going to be big or small [like with farsightedness or nearsightedness], it'll also be a distorted pattern."

5.2.5 Other Emergent Themes

Because this phase utilized the computer simulation during the concept introduction phase, it appears that students were triggered to discuss some properties of light that weren't brought up in other phases. This can, at least in part, be explained by the highly visual nature of the light and light rays in the computer program.

Light and Distance

The participants in this phase of the study often discussed properties of light in terms of the distance to the light. Strongly exhibited was the common p-prim that *closer is stronger* (diSessa, 1993), which could lead to the facet that *closer is brighter*. This led students to predict that the shape of the eye would affect the intensity of the image. As an example, one student predicted that because of the changing shape of the eye, the intensity of the grid pattern would change. When asked why, he responded simply "well, a flashlight doesn't look as bright at 20 feet as it does at 10 feet."

Another interesting response was how some students explained the fact that the spacing of the grid pattern changed as the shape of the eye changed. As one student explained,

> "If your light is really close – you have all of the light right here [the center of the lens], so your focal point is going to be pretty close too, because the light doesn't get very much. But if all your light comes from the whole direction - like they [light rays] are

> really far out [on the periphery of the lens] - then your focal point will be out further."

In this and other cases, the students seemed to be associating the spreading of light with the focal point. They described light that was close to the lens as entering mostly straight and at the center of the lens, while light that was farther away had time (or distance) to spread out and therefore hit the entire lens.

Light and Aberrations

When students were asked to test the effect of the aberration on the grid pattern and explain what they saw, an interesting explanation was provided. In conjunction with the above resource that *light entering a lens differently will focus differently*, students also discussed the changes to the grid pattern in terms of the spatial properties of the aberration. They described the deformed dots as "pointing away" or "moving away" from the location of the lens defect. They also noticed a spatial correlation between the grid and lens deformations. As one student explained

> "Well the bottom ones [dots] don't really change as much as the top ones. Like, if you push on the top, the top ones kind of have a tendency of coming down farther because the light angle changed. But the bottom ones don't' seem to have that much of a change because they're getting the direct light from the bottom of the lens."

Wavefronts

Throughout the entirety of the study only one student used the idea of wavefronts to describe the phenomena being discussed; that one student was a participant in this phase. The following excerpt illustrates her thinking:

> Interviewer: "All right, so why do you think those changes [to the grid pattern] might be happening?"
>
> Student: "Well, it has everything to do with the wavefronts. Once those wavefronts leave this light source [the flashlight], anything they hit could possibly change their shape, amplitude, period, everything. Once an effect like that happens, once it leaves there,

> it's going to continue on with whatever effect it had. Like, when this is coming in [light], hits this [eye lens] and changes waveform, it's going to come out changed – it's not going to be the same."

It should be noted that during the interviews, the device was referred to only as an 'aberrometer' to avoid activating the wavefront concept with students. Further examination of the transcript showed that even though this student's understanding of the wave nature of light was incomplete, she relied on it heavily as she continued to discuss the aberrometer. In the end, she came to nearly the same conclusions as the other participants who relied on only "light rays" and not the wave nature of light.

Converging and Diverging Lenses

The concept introduction had students explore the vision defects of near- and farsightedness, and how converging and diverging lenses could be used to correct those defects. Perhaps as a result of the emphasis on vision defects combined with students' lack of the general properties of lenses, an interesting result was found. During the second interview when students were asked to examine and describe a given lens (a convex lens, in fact), students often responded that the lens was "for nearsightedness" or "for farsighted people." As an example, consider the following example:

> Interviewer: "Here is a lens. Do you know what kind of lens that is?"
>
> Student: "Well, it looks like it's thicker through the middle. So that would be for the farsighted people – who can't see close."
>
> Interviewer: "Okay, so what does the lens do?"
>
> Student: "It redirects the light. So the light goes through and it changes the focal point back here in our eyes."

In this case, the student does not identify the lens by name or even in what way it affects the focal point, but instead associates it directly with one of the vision defects. Later in the interview, the student did bring up the term 'concave', but couldn't remember the other word or which lens was which. Further prompting with the terms 'converging' and 'diverging' enabled the student to remember that the two lenses did different things with the light; however light had to actually fall on the lens before the student was able to identify which lens had what purpose.

Another unfortunate result was found in the context of diverging lenses. The difference between convex and concave lenses, as described by one student in particular is that "Concave [lenses] focus light inward, convex focuses light outward." This confusion, in fact, occurred in more than one student. The notion that both lenses focus the light to a real image was exhibited by 6 of the 18 participants – a clear sign that the misconception was likely induced. In re-examining the computer simulation used by students during the concept introduction, it is clear that the diverging lenses are never dealt with individually – students never shine light through a diverging lens except when it is in series with a converging lens (such as the one in the eye). Because of this fact, it is understandable that students with no other prior knowledge about lenses would assume that the lens still creates a focal point. This issue was resolved, and no further evidence of this confusion was found in any other portion of the study.

5.2.5 Phase 2 Summary

Unlike the previous phase, this phase began with a concept introduction to basic optics and the function of the human eye. This provided a much more consistent background for the participants, and was designed to provide them with some of the resources that they would need to understand wavefront aberrometry. During previous phases, students who did not have this concept introduction were very disinclined to progress forward with the aberrometer. That type of reluctance from the participants did not surface during this phase. Presumably because of this concept introduction, the data obtained from the discussion of wavefront aberrometry provided a much richer set of data than did the previous phase. These contrasting experiences seem to verify that a basic understanding of light, lenses, and the eye is essential for the further understanding of wavefront aberrometry.

From the above analysis, it is evident that students do have a large number of resources of varying grain-size that they can use when constructing their understanding of wavefront aberrometry. Some resources, such as light moving through a lens, are exhibited by a large number of participants. Other resources are used less frequently, but are still important to study. Not surprisingly, significant scaffolding was at times necessary in order for students to activate appropriate resources and to associate them in meaningful ways. One example of scaffolding that seemed to help in this case was the drawing of light rays through a lens in order for them to think about what happened to the focal point. In many cases, this got students thinking about how the grid pattern would shift.

The primary implication for future phases is that a concept introduction in some form is necessary, and enables the study to continue forward. Students do seem to have an adequate number of resources to activate, which suggests that the study should progress with the intent to examine what scaffolding techniques enable to the most adaptive construction of knowledge of wavefront aberrometry.

Click here to read Phase 3 Description

5.3 Phase 3 Results

The third phase of the study dealt exclusively with students who were post-instruction in light, lenses, and basic geometric optics. Data was collectued in the semi-structured learning/teaching interview used throughout the study with groups of either two or three students. Interviews were conducted with five separate groups of students, with a total of 13 participants. The following are the resources that emerged from the data analysis. Because the students were post-instruction, the first subsection includes information that the students learned in the classroom setting as well as their prior knowledge.

5.3.1 Resources on Basic Principles of Light and Lenses

Because these students were post-instruction, they came to the group interviews with an extensive set of resources for the context of light and lenses. To probe their understanding, the initial questions focused on the function of the human eye, and produced the following themes. All of the groups indicated that vision defects were dependent on the shape of the eye, and 4 of the 5 groups indicated without being prompted which defect corresponded to which eye shape.

Light through Lenses

The students who participated in the group interviews utilized their resources about how light travels through lenses multiple times throughout the course of the interview. Consider the following excerpt as an illustration.

> Interviewer: “What do you think will happen to the grid pattern if I change the shape of the eye?”

> Student 1: “I think it may stay the same, as far as the structure of where the dots are. But they may get closer or farther, or the dots may change size also.”
>
> Interviewer: “Okay, why do you say that?”
>
> Student 2: “If it’s a nearsighted eye, the dots are going to get closer together because the light is going to be coming in more parallel compared to… like, the angle between the top one and how far the light is away is going to be … the further away the light is, the shallower the angle is. So here is the angle like that [draws it coming into the lens at a steep angle], so this dot is going to be higher. But if you pull all the light away, the angle is going to be shallower, so they’re all going to be closer together.”
>
> Student 3: “Yeah, based on the medium it goes through. Like they said, the angle is going through the medium, and based on the fraction, it’ll come out of the lens.”

As illustrated, students who participated in the group interviews used the idea of light travelling more frequently and more generally than any other of the previous participants. They also discussed the thickness of lenses in relationship to how light travels and the focal point of the lens. However, the *propagation of changes* p-prim that emerged in previous phases was not evident in this phase of the project.

The groups were also asked to perform the task of sketching light through lenses as was done in the earlier phases of the project. Every group indicated that the light would still focus if it entered from an angle, and that the focal point would shift in the same direction as the light entered (i.e. if the light entered the lens downward, the focal point would shift to below the original point). This is perhaps not surprising due to the fact that they had already studied light and lenses, and presumably were activate their resources appropriately in this context.

5.3.2 Shape of the Eye and Image Focus

As indicated above, all of the groups clearly stated that vision defects were a result of the shape of the eye and distance from the lens to the retina. The groups explained vision defects in terms of the person seeing a blurry object. As an example, consider the group discussion below.

> Student 1: “The distance from [lens] to [retina] would be different from eye to eye. If you want it to be in focus correctly, like if wasn’t a nearsighted eye or whatever. That’d be the difference between nearsighted and farsighted. Like if it … it’s supposed to focus back here [on the retina], but this [retina] is too far forward.”
>
> Student 2: “Yeah like, I’m pretty sure nearsighted means it focuses right here [in front of retina], so that you can’t see far objects. And farsighted is back here [behind retina] so you can’t see near objects.”

These students were discussing where the proper focus of the image would be located with respect to the location of the retina. Interestingly, none of the groups activated the resource that *the shape of the eye determines the image focus* during the discussion of the aberrometer. This is perhaps because they did not find the resource helpful in the given context. However, it may also be that the students did not have access to this resource as a useful tool, but instead knew it in a more factual, recall sense from their classroom experiences.

5.3.3 Shape of the Eye and Image Size

Unlike the previous resource, students did seem to rely heavily on the notion that *the shape of the eye determines the image size* when discussing the aberrometer. Three of the five groups predicted that the dots would change size when the shape of the eye was changed, and three groups also predicted that the overall size of the entire grid pattern would change. For example, the discussion from one group follows:

> Interviewer: “What do you think will happen to the grid pattern if I change the shape of the eye?”
>
> Student 3: “The lights wouldn’t be like, they’d either be tinier or bigger than they should be.”
>
> Interviewer: “Okay – the lights themselves or the whole pattern?”
>
> Student 3: “The whole pattern and the lights included.”
>
> Student 2: “Well, if you make [the eye] longer, probably from that distance the dots would spread out farther – the length between the dots would be farther.

And then after testing their predictions, the students noted

> Student 3: "yes, the pattern gets bigger as [the retina] gets closer … and close up its magnified, so it's so spread out that it's really hard to tell the brightness.

5.3.4 Other Emergent Themes

Several aspects of this phase were different than the previous phases, which contributed to some differences in terms of student responses. Perhaps most distinctive is that these students were asked to evaluate the Hartman-Shack computer simulation as their final task. Also, their post-instruction nature potentially contributed to some of the following resource uses.

Known Standard

Though the notion of a "standard" for comparison was raised by a few individuals in the prior phases of the study, every single group in this phase utilized this idea. When asked how the aberrometer functions, the students responded that your grid pattern should be compared to a grid pattern that was known to represent a "perfect" eye. This resource may be an extension of the commonly-held belief that perfect vision is 20/20 vision, and all vision defects are compared to this ideal vision. For example, one student explained that

"[The doctor] would base it off of what was normal. And then, what is wrong with your eye – he'd be able to tell. Because you can't really tell what is wrong with something until you have the normal."

Physics Equations

All groups also stated that the thickness of a lens affected where the focal point of the lens is located. Unlike previous phases of the study, however, these groups also relied on learned physics knowledge. For example, one group stated that "f=r/2" when explaining why the focal point depended on radius. Another group indicated that Snell's Law is what governed how light reflected through a lens, and also stated that light moved slower when it wasn't in a vacuum. Still another group recited the thin lens equation when explaining the location of the focused image with respect to an eye with a vision defect.

Computer Simulation Reactions

Overall, the students responded well to the computer simulation. The most commonly reported advantage of the simulation is that it is a more clear representation because the differences are more drastic and therefore more easily recognized; some students went so far as to call it 'more precise', and some liked that it got them to the final result more quickly than with the hands-on model. However they brought up an interesting drawback to the simulation: because of the two-dimensional representation, the students suggested that the simulation would be difficult to interpret without having previously seen the three-dimensional hands-on version first. One student used the representation of the screen to illustrate his point, saying that he wouldn't have realized it was a screen at all if he hadn't already seen it with the model.

Student resource activation was not studied in the context of the simulation; the simulation was added at the end of the protocol such that all other aspects were comparable across phases. Students utilized the visualization last, and as such already had constructed an understanding of the aberrometer before interacting with the visualization.

5.3.5 Phase 3 Summary

The participants in Phase 3 were post-instruction in light and optics from a traditional lecture course. As such, they had activated a significantly different set of resources than students from previous phases. Whereas the students who were pre-instruction tended to use more experiential knowledge, the post-instruction students used a considerable amount of textbook knowledge. Students on several occasions recited the thin-lens equation, and referred to the image and object distances as variables. However, they were able to appropriately activate resources in order to construct an understanding of wavefront aberrometry and in fact used some of the resources illustrated displayed in previous phases.

The results of this study indicate that the aberrometry protocol can be effectively used by students who have completed either the learning materials from this work or traditional instruction on light and basic geometric optics. It also provided a basis for the implementation worksheet to be used in a large lab setting.

Click here to read Phase 4 Description

5.4 Phase 4 Results

The final phase of this project was an implementation of the learning materials in the traditional lab setting. Students completed the worksheet using the same model of the eye, aberrometer set-up, and computer simulation as in all previous phases of the study. The individual worksheets provide another distinct situation in which to analyze student resources. The students who participated in this portion of the study used the same hands-on model and computer simulation as all prior participants, which provided a necessary point of comparison. However, the removal of the interviewer from the process enables us to examine the protocol as students understand and interact with the material on their own. The participants were post-instruction in light and optics, which removes a significant degree of variability in their prior knowledge and enables us to focus more closely on how they construct an understanding of wavefront aberrometry.

The data obtained from the worksheets are far less rich than the data obtained from the verbal interviews. This is in part due to the lack of opportunity to ask follow-up questions to more deeply probe student understanding. However, the information that they did write on the worksheet still provides data about their understanding of the eye as well as the aberrometer.

5.4.1 Comparison to Previous Phases

The students in this phase had learned the basics of light and lenses in their traditional lecture class, and as such were quite similar to the students in the previous part of Phase 3 who were interviewed individually. In terms of the initial part of the protocol dealing with light and lenses, these groups and the individuals who completed verbal interviews had no noticeable differences.

However, the students who were involved in our implementation study had not learned how light and lenses relate to the human eye and vision; the activities and worksheets served as their concept introduction for this topic. In this respect, the students were engaged in more discovery-based learning on these topics than their counterparts from the individual component of this phase, and as such these groups were more similar to the pre-instruction students from prior phases in this respect. Still, there were no noticeable differences between these groups, which seems to indicate that students are able to still construct a reasonably consistent understanding of the human eye, regardless of whether they complete the activities verbally or in a written open-ended worksheet format.

5.4.2 Other Emergent Themes

Several smaller themes emerged from these data, primarily because of the more independent nature of the worksheet format. These themes are explored below, and are compared to the previous research phases.

Answering "Why?"

Very frequently, the groups simply did not answer the part of the questions in which they were asked to explain why the particular phenomenon occurred. This can in large part be attributed to the lack of ability of the interviewer to ask a follow-up question. Also, the teaching assistants who were running the lab activities received no special training on these activities, and we therefore have no way of knowing to what level they attempted to engage the students or check on their progress through the activity period. Perhaps along the same lines, not many of the students responded in a full-sentence format to the questions. In future studies, this dilemma may be avoided by more carefully expressing what is expected of the students, and perhaps grading in such a way that they would be rewarded for answering all of the questions in their entirety.

Prediction Phase

One notable difference between the verbal and written implementations came during the prediction/testing phases of the protocol. The lab facilitators only provided the students with support when needed and took no action to ensure that the students were actually completing their predictions before conducting the experiment. As such, the responses from student worksheets indicates that the students were not necessarily actually making and testing their predictions. One exemplar prediction for the change due to the shape of the eye is as such:

> "If our eye was longer or shorter than normal, the grid pattern would be out of focus because the light would be converging before or after hitting the retina."

However, others were less convincing. For example, many groups wrote their predictions in a past-tense form, indicating that they had already tried the experiment. For example, one group stated as their prediction:

> "The images on the screen got smaller and sharper as the light source moved further away from the screen and larger as the light source moved closer. Due to the distance between the lens and retina."

In either prediction method, there seemed to also be a pattern of responses for the testing/explanation question, particularly with two very frequent responses. The first most frequent was a simple re-writing of the prediction. In many cases, the two answers were identical. Another frequent response is a statement such as "our prediction was correct." In both of these cases, the groups seemed to completely neglect the part of the question instructing them to address *why* the witnessed changes were happening as discussed above.

5.4.3 Phase 4 Summary

In this phase, students were post-instruction in light and optics, which provided more consistent data than was the case in Phase 2. The distinguishing feature of this study is that students completed the aberrometry protocol in worksheet format during their traditional lab section, and provided only written answers.

It is important to note that the worksheet data did not provide any information that was contradictory to what had been obtained throughout the rest of this study. In fact, students used many of the same resources to understand both the human eye and wavefront aberrometry. The following are examples of prominent resources found in other phases of the study that were also evident during this implementation phase:

- How the shape of a lens affects the image size, location, and focus
- How the shape of the eye affects the image size, focus, and location
- How light moves through a lens, and lenses dividing up and bending the light
- Ideas of subjectivity having only a component of "fairness"

Because of the large degree of agreement between this large set of data and the data from the previous phases, we believe that our previous analysis has been successfully confirmed. Also, the fact that no new themes emerged from this study leads to the belief that data saturation truly was achieved throughout the previous phases.

From this implementation phase, however, it was quite evident that verbal in-depth interviewing provided a much richer set of data than is obtained from open-ended qualitative worksheets, due in large part to the opportunity for asking follow-up questions in the interview setting. One can speculate that the richness of the data come solely from the fact that students simply did not provide as detailed of answers and was hoped; this could perhaps be fixed by more clearly delineating the requirements and properly aligning the reward structure to those requirements.

5.5 Chapter 5 Summary

This chapter provided a detailed look at how the data from this study were analyzed to determine what resources students use when constructing an understanding of the human eye and wavefront aberrometry. The three distinct phases of the study were analyzed in such a way to elicit the resources students used, but also so that comparisons could be made across all phases.

In general students had a large body of resources about the human eye and vision, many of which are artifacts of their everyday experiences with vision. As would be expected, students have significantly fewer resources initially available to them about wavefront aberrometry. However, this study indicates that students are able to construct the necessary understanding when appropriate scaffolding is provided. It appears that the students who were pre-instruction in light and basic optics were not prepared to construct an understanding of wavefront aberrometry – one might say that wavefront aberrometry fell outside of the students' Zone of Proximal Development (ZPD). However, wavefront aberrometry was within the ZPD of students who had some basic knowledge of light and optics. Some resources that students exhibit and were discussed in detail in this chapter include: how the shape of a lens relates to the size and focus of an image, how light moves through a lens and lenses 'dividing up' the light, and the nature of subjectivity/objectivity in diagnosis.

Click here to return to Chapter 4 or continue to Chapter 6

CHAPTER 6 - **Concept Categorization Analysis**

6.1 Adaptation for Physics Learning

The categorization scheme for concepts and the descriptions of concept links described in section 2.5.1 seem to provide the foundation for a complementary analysis method in which student understanding can be explored. The initial purpose of this study is to therefore determine the feasibility of using a meaningful understanding analysis in the content area of physics to elicit information about how students utilize and link concepts when constructing an understanding of a new situation or context. Once feasibility is assured, meaningful understanding analysis will be used to answer the following research questions: What types of concepts do students use when constructing an understanding of a new context, and in what ways do they link those concepts together? Specifically, what types of concepts do students use when constructing and understanding of wavefront aberrometry, and in what ways do they like those concepts together?

6.1.1 Concept Categorization

The categorization of concepts used by Lawson *et al.* (2000) and Nieswandt and Bellomo (2009) were developed for use in the context of biology. Details of these works are outlined in section 2.4. However, two difficulties arise when attempting to utilize this paradigm in the realm of physics, as outlined below. We believe these conflicts can be resolved without affecting the essence of the paradigm.

Observability

First, the defining characteristics involve the observability of the concept in time. For example, Lawson uses the example of fossil formation to describe how concepts can be observable in time, as further explained in section 2.4.1. This distinction is of little use in the context of physics, where the observability of an idea does not depend on how long one is able to watch. However, the notion of observability itself *is* a defining characteristic in the field of physics. Often the type of equipment or apparatus being used can affect how observable something is considered. For example, infrared light is not observable to our naked eye, but can be seen easily by putting on special goggles. Therefore, for the purposes of enabling meaningful understanding analysis to be useful in the context of physics, we propose the following operational definitions: *Descriptive concepts* are concepts that can be directly observed. They require no special apparatus or change of setup. *Hypothetical concepts* are those concepts that could be observed if given appropriate apparatus or setup, but are not directly observable. Finally, *theoretical concepts* are those concepts that cannot be observed, and no special apparatus or setup enables their observation.

Level of Expertise

The second issue that arises with the observability of concepts in physics is one of expertise. Consider the concept of "fossil" presented by Lawson, *et al.* as an example of a hypothetical concept (Lawson, et al., 2000). A fossil takes the same amount of time to be created regardless of who is "observing" the process, and therefore the concept is hypothetical to both novices and experts. As defined above, however, a concept's categorization in the context of physics is far more dependent on the level of expertise of the observer. Because a "concept" is actually a mental construct, and therefore not something that researchers can truly observe, it can be argued that no two people have an identical mental construct or "concept". However, it seems reasonable to assume that people who have similar mental models will have similar concepts and mental constructs. In this view, two experts in the field of physics will likely have similar mental constructs of an idea, and their constructs will be significantly different from the mental constructs of novices.

Consider the concept of a wavefront. A novice perhaps knows the textbook definition of a wavefront, but likely knows no way in which he could observe this phenomenon – any exemplars of the concept are therefore theoretical. On the other hand, an expert physicist understands wavefronts so deeply that observing an interference pattern is equivalent to observing the wavefronts of light – the expert is able to use descriptive exemplars of the concept. As a counter example, consider the notion of temperature. To an expert physicist, temperature is a measure of the average kinetic energy of the molecules of a substance – a concept with theoretical exemplars. However, to a novice physicist, temperature is how hot something is, which allows for descriptive exemplars of the temperature concept.

We believe these two examples illustrate the importance of considering the expertise-level when assigning concept categories. Because all participants in our study are introductory-level physics students, *all of our concept categorizations will be made from the viewpoint of the student, not the expert.* This also illustrates the necessity of predefining each term. In the previous example of wavefronts, the definition is clearly from the basis of light waves, and not water waves. In the same respect, one is only able to accurately categorize the concepts by first considering the definition being used for the concept. To remain consistent, the definitions of all concepts will also be taken from the point of view of the student, not the expert.

6.1.2 Analysis Approach

Unlike studies described by Lawson and colleagues and Nieswandt and Bellomo, no exemplary answers were predetermined for this study. The data used in this study were initially collected for the purpose of a study of how students transfer their physics knowledge to medical contexts. However, after the previous study was complete, this application of concept categorization was realized. Because the larger purpose is to examine knowledge construction, the data were primarily taken from student responses to prediction and explanation tasks.

Reliability Study of Analysis

Before data analysis began, a panel was assembled to test the reliability of the categorization scheme for different concepts. A list of the concepts used in the initial reliability study is included in the appendix. Each rater was given a list of the concepts that included the definition of each concept as listed in a popular introductory-level physics textbook, and asked to rate each concept based on the given definition. Prior to any discussion, the reliability among 5 raters was a very low 59%. The vast majority of discrepancies were of two types. The first discrepancy was in the qualitative versus quantitative nature of the concepts. For example, consider “speed”. One rater took this to mean “fast or slow” and therefore labeled it as descriptive, while another assumed it meant “10 mph” and therefore labeled it as hypothetical. Once all raters agreed to use the qualitative version for consistency, the reliability increased to 73% without further discussion. The second discrepancy was essentially rooted in the expert-like thinking of the rating panel; the panel consisted of graduate students and doctorates in the physics department. The issue came down to the difference between observing the concept, and observing the effect of the concept. The concept which elucidated this issue was “thermal conduction”. To a novice who knows only the definition (the transfer of energy due to the collision of atoms), this is a theoretical concept because he/she cannot possibly observe the atoms collide and transfer energy. However, some of the experts labeled this descriptive, and cited the example of feeling the warmth of a metal spoon in hot water. Once this notion was resolved and all raters agreed to think like novices, the reliability rose to a far more acceptable 93%.

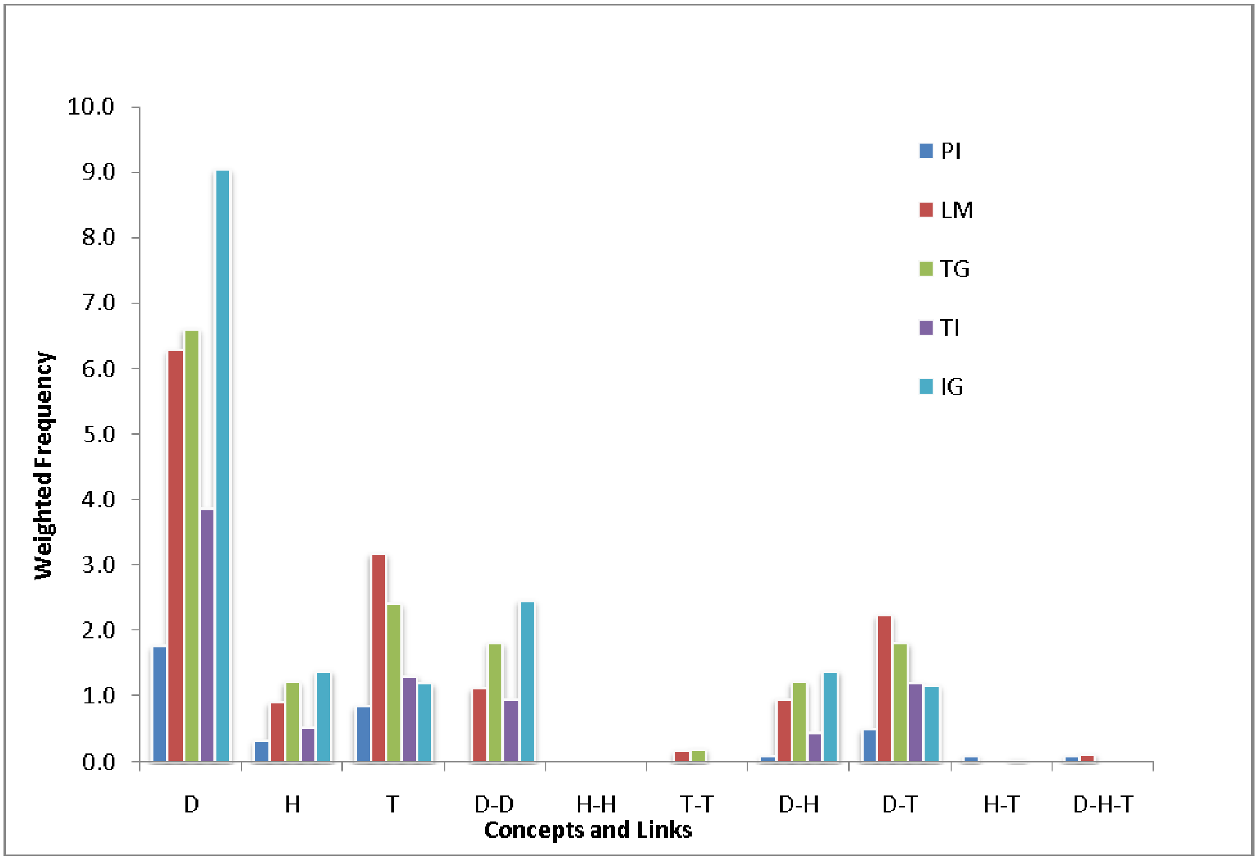
The collected data includes students' thinking on a variety of aspects of the application of optics to wavefront aberration as a diagnostic tool. In this feasibility study we limit our analysis to the students' responses to the questions "What do you think will happen to the grid pattern if the eye is not perfectly shaped [nearsighted/farsighted]?", and "What do you think will happen to the grid pattern if the lens of the eye has a defect [aberration]?". Students were asked to make and explain predictions for each of these questions, to test their predictions, and reconcile any discrepancies.

6.2 Results

The population of this study is the same as those described in section 3.3.2. The first set of students contained 12 participants who were interviewed individually and were pre-instruction in light and basic geometric optics; they are labeled as PI for pre-instruction individuals. The second set, 18 participants, was interviewed twice. The first meeting allowed students to work through an exploratory lesson in which they used hands-on activities and computer simulations to learn about the light, vision, and the human eye. The second meeting was a learning/teaching interview which followed the same protocol used in all other parts of this study. They will be labeled LM to designate that they used the learning materials. The third and fourth sets were both post-instruction in light and basic geometric optics, as they had learned the material in a traditional lecture and lab setting. The third set was made of 5 groups (13 total participants); the fourth set contained 30 participants who completed the protocol in the form of written extended-response questions. These sets are labeled as TI and TG for traditional instruction individuals and groups, respectively. Finally, the students who participated in the implementation phase while working in groups are labeled as IG.

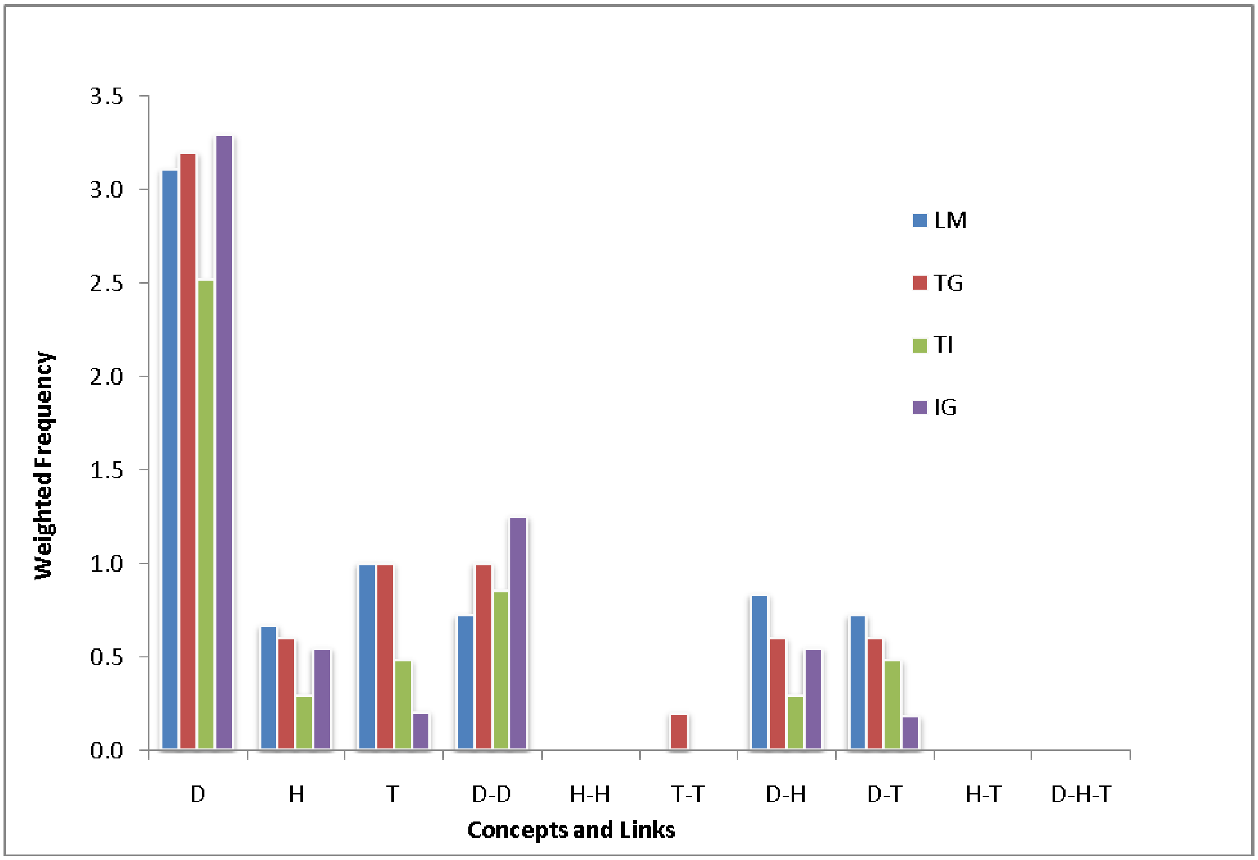
Presented in the remainder of this chapter is an analysis of the types of concepts that students used, as well as the links they created. Recall that concepts can be of three types: descriptive, hypothetical, or theoretical. Concept links can be created at a variety of levels as well: single-level links (descriptive-descriptive, theoretical-theoretical), cross-level links (descriptive-theoretical, hypothetical-theoretical), or the more complex multi-level links in which all three concept types are linked to form a single thought or idea.

Figure 6.1 Weighted data of concepts and links, aberrations and vision defects combined



Shown in Figure 6.1 is a histogram illustrating student concept and link use. Individuals who completed our learning materials on the human eye (LM) and the sets from traditional-instruction classes (TI and TG) used more concepts and created more links than the other two sets, and in fact the pre-instruction individuals (PI) were the lowest in every category (as we might expect). Upon examining the transcripts, we found that the students who were interviewed in groups routinely played off of each other's ideas and came to a consensus on the questions as a group and not individually. The success of the groups to create and link concepts is supported by work done on student learning in small groups (Springer, Stanne, & Donovan, 1999). Because a great deal of research has been conducted illustrating that research-based interactive learning strategies enable students to build a more coherent knowledge structure and more superior conceptual understanding, the lack of distinction between the TI/TG and LM groups is surprising (Corpuz, 2006). To look at the data more closely, we can separate out the two topics: Near/farsightedness (Figure 6.2) and Aberrations (Figure 6.3).

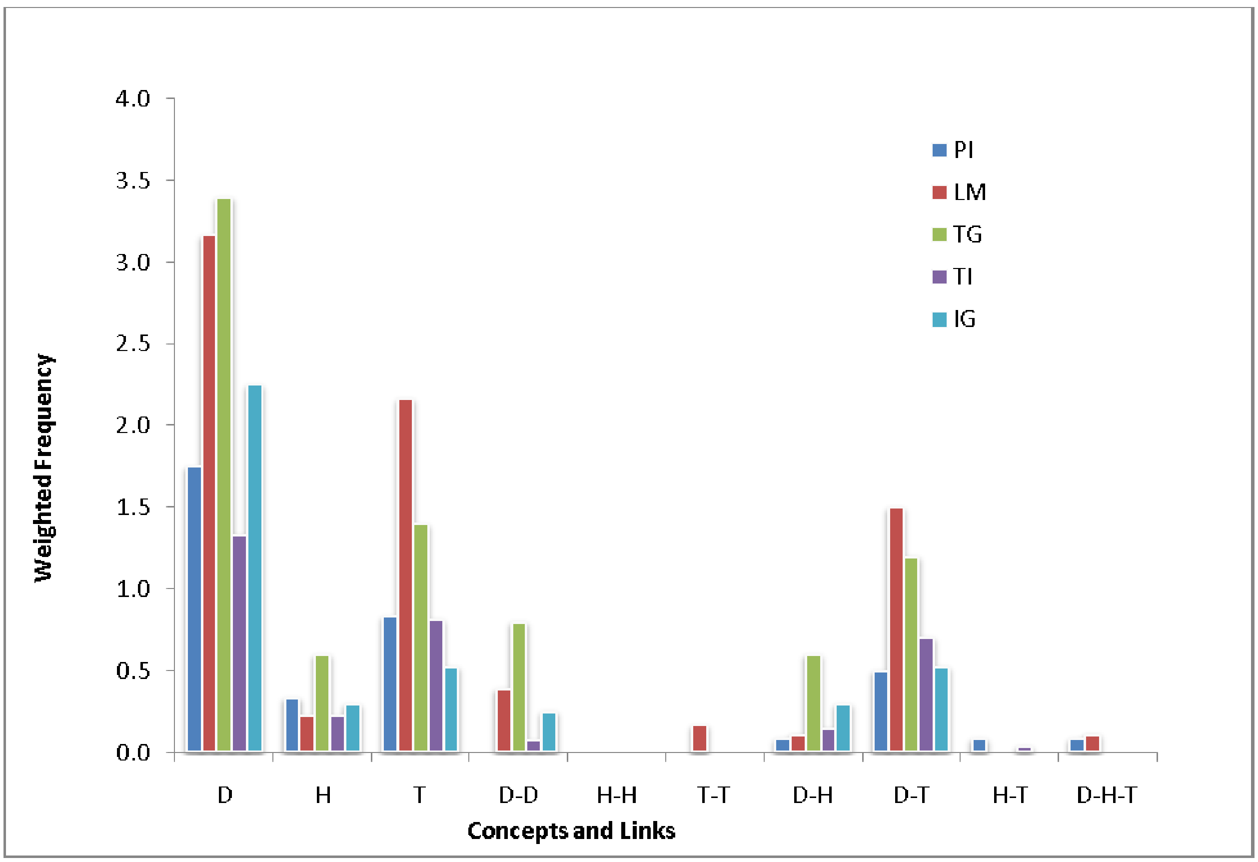
Figure 6.2 Weighted data of concepts and links for near/farsightedness



The results for Near/farsightedness show a decreased gap between the individuals using reformed instruction and individuals using traditional instruction in terms of the types of concepts they used, as well as in the links between concepts. (Note that the pre-instruction individuals were not directly asked this question, and data for that subset are therefore not reported.) The decrease in disparity among subsets is not so surprising when one considers that nearsightedness and farsightedness are common conditions – all students likely have some ideas about these defects, and therefore have more resources that they can apply to this situation. Still, little evidence indicates the ability to link the higher-level concepts for any group, which indicates that their understanding is likely not complete or profound.

The most commonly used idea among all participants is that 'the shape of the eye affects the spacing of the grid pattern', which is a link between two descriptive concepts. Also commonly used was another single-level descriptive link, 'the shape of the eye affects how in-focus the dots are'; this link was most commonly used by the traditional instruction individuals who tended to place a great deal of emphasis on how clear the image appeared. All of the hypothetical concepts used in answering this question were about the location of the focal point of the lens – the most common link was that 'the shape of the eye changes the location of the focal point.' In the case of three traditional-instruction individuals, they stated this relationship in terms of the variables in the thin lens equation by saying 'the d_o changes, so the d_i must change also [since the focal point of the lens does not change].'

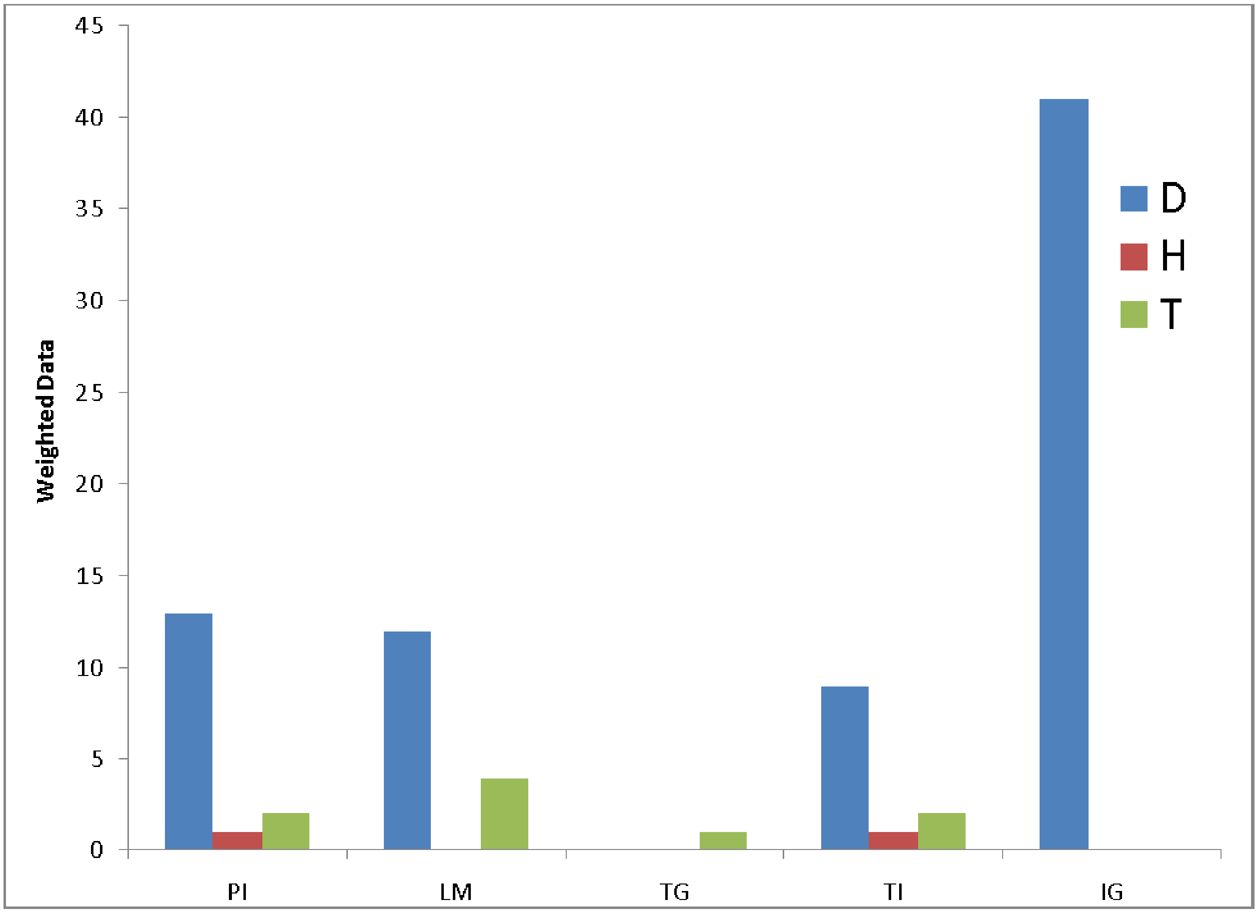
Figure 6.3 Weighted data of concepts and links for aberrations



In the context of lens aberrations, we see that the gap between groups is much wider. The idea of aberrations in a lens was new to all subsets, and therefore we expect that they would have fewer resources to use in this context. However, we found that students use far more theoretical concepts and are able to link them to descriptive concepts. Further examination revealed that these theoretical concepts dealt primarily with the propagation of light and were frequently linked to the visible changes on the grid pattern. From this perspective, the post-instruction subsets had more resources because they had learned about how light propagates in terms of lenses, mirrors, and refraction. A significant number of participants stated that 'the aberration changes the direction of light through the lens' and even more were able to make the cross-level link that 'the direction of light through a lens changes the position of the image.' Hypothetical concepts were used most infrequently – again pertaining to the location of the focal point – and were rarely linked to other concepts of any type. Another interesting thing to note is that a couple students did display the ability to create a multi-level link in this context, whereas they did not in the near/farsighted context.

Also of interest are the concepts which students stated, but failed to link together. The final chart shows a weighted frequency analysis of these unlinked concepts. The pre-instruction students display the most unlinked concepts, whereas the groups had no unlinked concepts. Initially surprising is that the vast majority of unlinked concepts are descriptive. This can be explained, particularly with the pre-instruction individuals by examining the exact responses. During the prediction phases, we find that students tended to list some characteristics of the grid pattern that might change without explaining why they thought those changes would occur. In this respect, students were taking a "birdshot" approach to their predictions – throw a bunch of things out there, and see what sticks. This type of response pattern has been studied previously, for example by Otero in the context of magnetism (Otero, 2006). Similarly, they simply stated the changes in appearance of the grid pattern during the observation phases without attempting to explain. Two examples of such statements are 'the grid pattern gets blurrier", or "the dots move." The graph also shows that the majority of unlinked concepts were stated during the discussion of aberrations, and very few during the near/farsightedness discussion. This is consistent with the earlier hypothesis that because students are more familiar with near/farsightedness, they have more resources at their disposal than they do for the context of aberrometry.

Figure 6.4 Weighted data of unlinked concepts



6.3 Chapter 6 Conclusions

From the data presented above, a few general conclusions can be drawn. One can immediately see that descriptive concepts were the most heavily used and that very few hypothetical concepts were utilized and linked. This result indicates that students relied most heavily on lower-level concepts and agrees with previously conducted studies by Lawson, *et al.* and Nieswandt and Bellomo. Students were able to use a larger number of concepts during the discussion of nearsightedness and farsightedness, perhaps because of their familiarity with the topic. Students utilize some of the resources necessary to understand wavefront aberrometry and thus transfer their learning from other topics to this previously unfamiliar topic. However, they rely most heavily on descriptive concepts. Thus, while students seem to understand and transfer the material which was learned in other contexts to this new context, they do not necessarily have as *deep* an understanding of the phenomena as one would hope.

Students were also more likely to link lower-level concepts than to create higher-level or cross-level links. Again, this distinction is clear when examining nearsightedness and farsightedness as compared to aberrometry. While students were able to utilize some theoretical concepts in describing aberrometry, all students tended to use the same theoretical concept – light moving through a lens. The aberrometry data illustrate a clear distinction between those who had learned about how light propagates (TI and TG) and those who had not. Much greater variety of the concepts at all levels were used when discussing near/farsightedness. Thus, we can conclude that participants had a wider body of knowledge and thus a deeper understanding of the resources on this topic.

Beyond the data presented here in the context of vision and wavefront aberrometry, this study provided significant information pertaining to the implementation of this newly-developed analysis technique. First and most generally, it appears that this method is valuable for obtaining information about what types of concepts students utilize and the ways in which they link those concepts together. Both interview (verbal) and written data provided adequate information for this type of analysis.

Further, the analysis provides evidence of clear distinctions among different types of students. In our study, we investigated the resources that students with different backgrounds were able to utilize when applying physics to a new context. For vision defects which are somewhat familiar to everyone the differences among the groups was noticeable but somewhat smaller than for wavefront aberrometry. Thus, the method provides a good way to look at differences in student thinking when they apply physics to a new situation. Also, this method can be used in any range of physics contexts.

The primary disadvantage of this analysis method is that for some purposes, this method may not provide a wide-enough spectrum of information. For example, perhaps one would like to know *why* a particular concept was used, or what triggered the student to associate two concepts. In order to obtain that information, supplementary analysis should be conducted, as was presented in the analysis section of this paper. However, this does not take away from the value of the analysis method for the intended purpose. Because the researcher (who is often an expert in the field) is attempting to think like a novice, it can potentially take time to establish a coding process that represents how we would expect novice students to categorize and link the concepts. However, once this coding is created, the process progresses relatively quickly.

This method of concept analysis provides some significant insights into the ways in which students utilize previous learning. First, it provides a method for distilling a large body of data into simple, discrete pieces – the concepts. It also allows the researcher to view how those pieces are being connected – the concept links. Not only does it allow for the identification of which concepts students are using during the process of transferring learning, but enables us to see the level of understanding, the order in which the concepts are used and how the students associate the concepts with each other. This process affords the possibility of creating a record or map of how students activate and associate different resources. It also like has the potential to allow for the study of when students activate and associate the different concepts over the course of the learning process. Thus, we can obtain a rather clear picture of the level at which students are able to use previously learned material in new learning situation. By comparing the students' utilization of concepts with a desired level, we can identify appropriate types of scaffolding that can aid in the transfer process and help students develop an understanding that could better match our learning goals of deep or thorough understanding.

CHAPTER 7 - **CONCLUSIONS**

The purpose of this project was to examine how students construct an understanding of a topic in physics that is unfamiliar to them. As part of a broader investigation in the transfer of learning in physics this study investigated how students used existing knowledge and mental resources when attempting to explain an unfamiliar application. The context was wavefront aberrometry and how students transfer knowledge of light and basic geometric optics when constructing their understanding.

7.1 Overview of the Study

This research project was conducted at Kansas State University from 2005-2009. The majority of the participants were enrolled in an introductory physics course; most participants were enrolled in the algebra-based physics course which has a high concentration of life-science majors including pre-medicine and pre-veterinary students.

The first phase of the study was a pilot test in which I used clinical interviews to explore student models of the human eye. An open-ended qualitative survey was used to corroborate the information learned from the pilot study. Finally, I began conducting pre-instruction, semi-structured interviews that dealt with the topic of wavefront aberrometry.

During the second phase, two-part teaching and learning interviews were conducted with students who were enrolled in the algebra-based introductory physics course and who had not yet received any instruction in optics. The first part of the interview allowed us to work through the topics of basic optics and vision with the students, which enabled more productive discussions of aberrometry during the second interview. This process allowed for much richer data of student knowledge construction, as all participants were then primed to discuss the more difficult topic of wavefront aberrometry. Throughout the second phase, scaffolding activities meant to assist students were created and tested repeatedly in order to determine what scaffolding activities were appropriate for the given context.

Participants in the third phase of the project were post-instruction in light and basic geometric optics; as such, only one interview was necessary and could be focused entirely on the concepts of wavefront aberrometry. During this phase, we were able to study not only how students constructed an understanding of wavefront aberrometry, but also what variations exist among the models they built.

The fourth and final stage of the project involved an implementation of the learning materials that were developed as a result of the first three phases. The interview protocols were modified to the form of an open-ended worksheet and were administered in a large, traditional laboratory setting. This implementation provided the opportunity to see how students would interact with the learning materials, and confirmed that the data from previous phases had reached saturation.

7.2 Comparison of Results across Phases

When looking across all phases of this study, some trends are immediately apparent. All of the participants had at least some basic knowledge about vision. Given our everyday experiences with sight, it is reasonable that students would have resources that help them understand the eye and vision. However, it is clear that students do not necessarily have an expert-like model of how the eye works.

A wider range of available resources exists for the ideas of light and basic optics, including lenses. The participants who were pre-instruction in light and optics and who did not complete our learning materials on the human eye had far fewer resources for understanding light and lenses. The post-instruction students or those who completed our learning material on light and optics had many more resources at their disposal, and therefore were able to form a more complete understanding of the human eye and vision.

Perhaps because of their lack of available resources, the pre-instruction students showed great hesitation when talking about the aberrometer. They were less likely to make predictions, and often stated that they could not postulate an explanation for the operation of the instrument. On the contrary, the post-instruction students were more willing to make and test predictions, postulate explanations, and make connections to prior knowledge. As such, a much richer set of data came from students who were post-instruction or who had completed the learning materials on the human eye.

7.3 Research Questions

7.3.1 Research Question #1

What resources do introductory-level students use to understand light and optics, and what variations exist between their models?

This study indicates that students have a large body of resources that help them understand light and basic optics. They also have clear ideas about how the human eye functions.

Participants from all phases of the study used the resource that *light moves in a straight line*. Evidence included the many ray drawings that student made, and particularly the total lack of student drawings of light as a wave. Post-instruction students were able to draw traditional ray diagrams, yet even the pre-instruction students illustrated light as a straight line even if they did not call it a 'ray.' The participants had previously-acquired resources about lenses, as well. One such resource is the idea that *lenses break up the light.* Many students knew that lenses affected the light that went through them, though there was sometimes confusion about what each lens did. Though students often said that they knew one of the lenses focused the light, many confused the properties of concave and convex lenses. We also discovered that pre-instruction students did not understand the physical meaning of a concave lens diverging the light.

Students also have an interesting set of resources that they use to understand the human eye. Most students view the eye as a simple lens with a screen (retina). An expert would realize that a fixed lens does not provide the human with ability to see things at a range of distances; however, in the students had no such cognitive conflict about their models until it was induced by the researcher. In terms of vision defects, two subsets of resources were used. Some students believed that vision defects such as nearsightedness and farsightedness were a result of a deficient lens. Other students recognized that the shape of the eye affected vision and caused the vision defects. Not surprisingly, the students with the most accurate models tended to be those who suffered from a vision defect themselves.

7.3.2 Research Question #2

To what extent can students apply their knowledge of light and optics to construct an understanding of wavefront aberrometry, and what scaffolding activities can be utilized to aide their knowledge construction?

Students who were pre-instruction in light and basic optics had a difficult time understanding wavefront aberrometry, in part because of their lack of confidence with the background material as well as because of their lack of adequate prior resource to activate. However, after a simple concept introduction, students were able to draw upon a large body of information that they relied on when constructing a model of wavefront aberrometry.

Students used many resources about light and optics to help them understand the aberrometer. One particularly interesting set of resources surrounds the idea that *light entering a lens differently will exit differently.* Students used this resource to explain why the dots of the grid pattern were shifted due to aberrations, and to describe why they viewed the light through the aberration as being somehow scattered. They also used the resource that *the shape of a lens determines the image focus* when dealing with aberrations. In fact, some students described an aberration as possibly being a spot on a lens that was concave, and therefore caused the light to diverge in that one place.

In terms of how an aberrometer could diagnose vision defects, many students used the idea of a *known standard.* In this respect, the students proposed that the aberrometer would not be useful unless you knew what the output was supposed to look like for a perfect eye. Also, students seem to have varying ideas about the concepts of subjectivity and objectivity. Many students view objectivity as only having a component of 'fairness', and as such had difficulty resolving the difference between objective and subjective diagnosis methods. However, students seemed to eventually see the value in a diagnosis system in which there could be no human interpretation, and therefore greater accuracy.

The necessary scaffolding differed between participant groups, as the pre-instruction students required more assistance with their model construction. However, the required scaffolding for the post-instruction students was quite consistent. The areas in which scaffolding was most necessary are as follows:

- How light moves through lenses
- How aberrations affect the light

- How the grid pattern can be interpreted

7.4 Transfer of Learning

In this study, transfer of learning is examined from the point of view of student knowledge construction instead of a pre-determined set of information; this creates a student-centered view of transfer. It also regards transfer as a dynamic process in which students are evaluated during the learning process. In this framework, any prior knowledge that a student uses during the learning process is considered. The results also align with the two-level frame work presented by Redish and expanded upon by Rebello *et al.* (2005) in which associations are created between a source (the basic optics) and a target (wavefront aberrometry).

The results from this study are consistent with similar studies on transfer of learning that indicate that students are able to transfer information in two different ways: either spontaneously or with the assistance of scaffolding activities (Aryal, 2007). However, due to the varying degrees of prior knowledge about basic optics and the human eye, this study primarily recorded instances of scaffolded transfer. This corresponds with research by Corpuz which noted a difference in student learning trajectories as a function of their Zone of Proximal Development (ZPD) (2006).

7.5 Unanswered Questions

Though this work has provided considerable insight into student knowledge construction, resource use, and transfer, several questions remain unanswered. First of all, these studies were conducted with students at the algebra-based introductory level; it would be interesting to see how useful the developed materials would be for other levels, such as conceptual or calculus-based courses.

Because the essence of wavefront aberrometry can be obtained by using only geometric optics, we did not discuss any physical optics. Knowledge of the wave nature of light is necessary for understanding the details of the diagnosis, it would be potentially valuable to examine if and how the wave picture of light and the idea of wave fronts could be incorporated.

In terms of the concept categorization analysis presented in Chapter 6, many further questions have arisen. The analysis technique provided a beneficial method of extracting quantitative data from the qualitative interviews, and allowed for the analysis of what types of concepts students use and how they link concepts. However, the question arises: is it possible to track a student's concept use over time? Perhaps students are able to use concepts and create links at different levels at different times over the course of the learning process. Also, the question of how students' concepts and concept links compare with those of 'experts' is as yet unanswered. This knowledge could allow for the development of teaching materials which provide scaffolding at the appropriate conceptual level, while also encouraging the timely transition to higher-level concept use.

7.6 Conclusions

Prior to this research, the main body of literature on student understanding in this topic focused primarily on image formation and basic geometric optics, with very little emphasis on how students understand the eye (McDermott & Redish, 1999). This study investigated student understanding of vision and basic optics, and went on to examine how students were able to transfer that knowledge and construct and understanding of wavefront aberrometry, and as such has considerably expanded on the body of literature. Further, this study has provided deeper insight into how students transfer prior knowledge to new situations and context and what scaffolding activities encourage useful and appropriate transfer.

In terms of research on student understanding, this work provides information on student learning that extends beyond the context of wavefront aberrometry. By studying how students transfer existing knowledge and activate resources in order to construct an understanding of a new context, we can better understand how to scaffold student learning. This process of developing and testing scaffolding can therefore have a profound effect on how curricular materials are developed and tested, and ultimately lead to improved instruction.

REFERENCES

ALOP Asia (2006, November 6-11, 2006). Paper presented at the Fourth UNESCO Workshop on Active Learning in Optics and Photonics, Delhi, India.

Ambrose, B. S., Heron, P. R. L., Vokos, S., & McDermott, L. C. (1999). Student understanding of light as an electromagnetic wave: Relating the formalism to physical phenomena. *American Journal of Physics, 67*(10), 891-898.

Ambrose, B. S., Shaffer, P. S., Steinberg, R. N., & McDermott, L. C. (1999). An investigation of student understanding of single-slit diffraction and double-slit interference. *American Journal of Physics, 67*, 146-155.

Andersson, B., & Karrqvist, C. (1981). Light and its properties: EKNA Report #8. Sweden: Goteborgs University.

Arell, A., & Kolari, S. (1978). Experiments on a model eye. *American Journal of Physics, 46*(6), 613-614.

Aryal, B. (2007). *Transfer of learning with an application to the physics of positron emission tomography*. Kansas State University, Manhattan, KS.

Atchinson, D. A. (2005). Recent advances in measurement of monochromatic abberations of human eyes. *Clinical and Experimental Optometry, 88*(1), 5-27.

Ausubel, D. P. (1977). The facilitation of meaningful verbal learning in the classroom. *Educational Psychologist, 12*(2), 162-178.

Bassok, M. (1990). Transfer of domain-specific problem-solving procedures. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 522-533.

Bendall, S., Galili, I., & Goldberg, F. (1993). Prospective elementary school teachers' prior knowledge about light. *Journal of Research in Science Teaching, 30*, 1169-1187.

Bennet, A. G., & Rabbetts, R. B. (1989). *Clinical visual optics* (2 ed.). Oxford: Butterworth-Heinemann.

Biedermann, K. (2002). The Eye, Hartmann, Shack, and Scheiner. In H. J. Caulfield (Ed.), *Optical information processing: A tribute to Adolf Lohmann* (pp. 123-130). Bellingham, Washington: SPIE Press.

Born, M., & Wolf, E. (1989). The diffraction theory of aberrations *Principles of optics: Electromagnetic rheory of propagation, interference, and diffraction of light* (6th ed ed., pp. 459-490). New York: Pergamon Press.

Bransford, J. D., & Schwartz, D. (1999). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education, 24*, 61-100.

Brown, A. L., Bransford, J. D., Ferrera, R. A., & Campione, J. C. (1983). Learning, remembering and understanding. In M. J. H. Flavell (Ed.), *Handbook of Child Psychology* (Vol. 3 - Cognitive Development). New York: Wiley.

Brown, A. L., & Kane, M. J. (1988). Preschool children can learn to transfer: Learning to learn and learning from example. *Cognitive Psychology, 20*, 493-523.

Bruner, J. (1966). *Toward a theory of instruction*. Cambridge: Harvard University Press.

Case, R. (1992). Neo-Piagetian theories of child development. In R. J. Sternberg & C. A. Berg (Eds.), *Intellectual Development*: Cambridge.

Charmaz, K. (2006). *Constructing Grounded Theory: A practical guide through qualitative analysis*. Thousand Oaks: Sage.

Chen, Huang, J., & Loh, E. (1987). Computer-assisted teaching of optics. *American Journal of Physics, 55*(12), 1129-1133.
Chen, Z., & Daehler, M. W. (1989). Positive and negative transfer in analogical problem solving. *Cognitive Development, 4*, 327-344.
Chi, M. T. H., & Roscoe, R. D. (2002). The process and challenges of conceptual change. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice*. Dordrecht: Kluwer.
Cobb, P. (1994). Where is the mind? Constructivist and Sociocultural perspectives on mathematical development. *Educational Researcher, 23*(7), 13-20.
Cohen, L., & Manion, L. (1994). *Research methods in education* (4 ed.). New York: Routledge.
Colicchia, G., & Wiesner, H. (2006). Measuring aberration of the eye with wavefront technology. *Physics Education, 41*(4), 307-310.
Corbin, J., & Strauss, A. (1990). Grounded theory method: Procedures, canons, and evaluative criteria. *Qualitative Sociology, 13*(1), 3-21.
Corpuz, E. (2006). *Students' modeling of friction at the microscopic level.* Unpublished Dissertation, Kansas State University, Manhattan, KS.
Creswell, J. W. (1998). *Qualitative inquiry and research design; Choosing among five traditions*. Thousand Oaks, CA: Sage.
de Brabander, J. (2004). Wave front technology - Part 1. *Global CONTACT Magazine,* 32-35.
diSessa, A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2-3), 105-225.
diSessa, A., & Sherin, B. L. (1998). What changes in conceptual change? *International Journal of Science Education, 20*(10), 1155-1191.
diSessa, A., & Wagner, J. (2005). What coordination class has to say about transfer. In H. P. Mestre (Ed.), *Transfer of Learning from a Modern Multidisciplinary Perspective*. Greenwich, CT: Information Age Publishing.
Duit, R. (2007). Bibliography - STCSE: Students' and Teachers' Conceptions and Science Education. http://www.ipn.uni-kiel.de/aktuell/stcse/bibint.html
Edwards, T. H., & et al. (1975). Life science-related physics laboratory on geometrical optics. *American Journal of Physics, 43*(9), 764-765.
Englehardt, P. V., & Corpuz, E. G. (2003). *The Teaching Experiment - What it is and what it isn't.* Paper presented at the Physics Education Research Conference, Madison, WI.
Eylon, B. S., Ronen, M., & Ganiel, U. (1996). Computer simulations as tools for teaching and learning: Using a simulation environment in optics. *Journal of Science Education and Technology, 5*(2), 93-110.
Farkas, N., Donnelly, K. M., Henriksen, P. N., & Ramsier, R. D. (2004). The blind spot: Re-educating ourselves about visual images. *Physics Education, 39*(3), 294-297.
Festinger (1957). *A Theory of Cognitive Dissonance*. Stanford, CA: Standford University Press.
Galili, I., Bendall, S., & Goldberg, F. (1993). The effects of prior knowledge and instruction on understanding image formation. *Journal of Research in Science Teaching, 30*, 271-301.
Galili, I., & Hazan, A. (2001). The effect of a history-based course in optics on students' views about science. *Science and Education, 10*(1-2), 7-32.
Galili, I., & Lavrik, V. (1998). Flux concept in learning about light: A critique of the present situation. *Science Education, 82*(5), 591-613.
Gay, L. R., Mills, G. E., & Airasian, P. (2006). *Educational Research: Competencies for Analysis and Applications* (8 ed.). Upper Saddle River, NJ: Pearson Education.

Gentner, D., & Stevens, A. L. (1983). *Mental Models* Hillsdale: Lawrence Erlbaum.
Giancoli, D. C. (2005). *Physics Principles with Applications* (6 ed.). Englewood Cliffs, NJ: Prentice Hall.
Gilbert, J. K., & Boulter, C. J. (1998). Learning Science through models and modeling. In K. Tobin & B. Frazer (Eds.), *International Handbook of Science Education*. New York: Springer-Verlag.
Glaser, B., & Strauss, A. (1967). *The discovery of grounded theory*. Chicago: Aldine.
Glick, M. L., & Holyoak, K. J. (1998). Learning science through models and modeling. *Cognitive Psychology, 12*, 306-355.
Goldberg, & McDermott, L. C. (1987). An investigation of student understanding of the real image formed by a converging lens or concave mirror. *American Journal of Physics, 55*, 108-119.
Goldberg, F., & Bendall, S. (1995). Making the invisible visible: A teaching/learning environment that builds on a new view of the physics learner. *American Journal of Physics, 63*, 978-991.
Goldberg, F., Bendall, S., & Galili, I. (1991). Lenses, pinholes, screens and the eye. *The Physics Teacher, 29*(221-224).
Goldberg, F., & McDermott, L. C. (1986). Student difficulties in understanding image formation by a plane mirror. *The Physics Teacher, 24*, 472-480.
Grayson, D. J. (1995). Many rays are better than two. *The Physics Teacher, 33*, 42-43.
Greca, I. M., & Moreira, M. A. (2002). Mental, physical, and mathematical models in the teaching and learning of physics. *Science Education, 86*(1), 106-121.
Greeno, J. G., Moore, J. L., & Smith, D. R. (1993). Transfer of Situated Learning. In D. K. Detterman & R. J. Sternberg (Eds.), *Transfer on Trial: Intelligence, cognition and instruction*. Norwood, N.J.: Ablex.
Halliday, D., Resnick, R., & Walker, J. (2008). *Fundamentals of Physics* (8 ed.): John Wiley & Sons.
Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics Physics Education Research Supplement, 68*(S1), S52-S59.
Hammer, D., & Elby, A. (2002). On the Form of a Personal Epistemology. In B. K. Hofer & P. R. Pintrich (Eds.), *Personal Epistemolgy: The Psychology of Beliefs about Knowledge and Knowing* (pp. 169-190). Mahwah, NJ: Erlbaum.
Hammer, D., Elby, A., Scherr, R., & Redish, E. F. (2005). Resources, Framing, and Transfer. In H. P. Mestre (Ed.), *Transfer of Learning from a Modern Multidisciplinary Perspective*. Greenwich, CT: Information Age.
Hewitt, P. G. (2006). *Conceptual Physics*. New York: Pearson.
Johnson-Laird, P. N. (1983). *Mental Models: Towards a cognitive science of language, inference, and consciousness*. Cambridge, MA: Harvard University Press.
Jones, B. W. (1976). Optics - what to teach? *Physics Education, November*(513), 517.
Karplus, R. (1977). Science Teaching and the Development of Reasoning. *Journal of Research in Science Teaching, 14*(2), 169-175.
Langley, D., Ronen, M., & Eylon, B. S. (1997). Light propogation and visual patterns: preinstruction learners' conceptions. *Journal of Research in Science Teaching, 34*, 399-424.

LaRosa, C., Mayer, M., Patrizi, P., & Vicentini-Missoni, M. (1984). Commonsense knowledge in optics: Preliminary results of an investigation into the properties of light. *European Journal of Science Education, 6*, 387-397.

Lave, J., & Wenger, E. (1991). *Situated Learning: Legitimate peripheral participation*. Cambridge: Cambridge University Press.

Lawson, A. E., Abraham, M. R., & Renner, J. W. (1989). *A theory of instruction: Using the learning cycle to teach science concepts and thinking skills.* Paper presented at the National Association of Researchers in Science Teaching, Cincinnati, Ohio.

Lawson, A. E., Alkhoury, S., Benford, R., Clark, B. R., & Falconer, K. A. (2000). What Kinds of Sceintific Concepts Exist? Concept Construction and Intellectual Development in College Biology. *Journal of Research in Science Teaching, 37*(9), 996-1018.

Lawson, A. E., & Renner, J. W. (1975). Relationships of concrete and formal operational science subject matter and the development of the learner. *Journal of Research in Science Teaching, 12*(4), 347-358.

Lawson, A. E., & Thompson, L. D. (1988). Formal reasoning ability and misconceptions concerning genetics and natural selection. *Journal of Research in Science Teaching, 25*(9), 733-746.

Lobato, J. E. (1996). *Transfer Reconceived: How "sameness" is produced in mathematical activity.* Unpublished Ph.D. Dissertation, University of California, Berkeley, Berkeley, CA.

Lockhart, R. S., Lamon, M., & Glick, M. L. (1988). Conceptual transfer in simple insight problems. *Memory and Cognition, 16*, 36-44.

Marton, F. (1986). Phenomenography—a research approach to investigating different understandings of reality. *Journal of Thought, 21*, 28-49.

McDermott, L. C., & Redish, E. F. (1999). Resource Letter: PER-1: Physics Education Research. *American Journal of Physics, 67*(9), 755-767.

McDermott, L. C., & Shaffer, P. S. (2002). *Tutorials in Introductory Physics*. Upper Saddle River, NJ: Prentice Hall.

Mertens, D. M. (2005). *Research and Evaluation in Education and Psychology* (2 ed.). Thousand Oaks, CA: Sage.

Minstrell, J. (1982). Explaining the 'at rest' condition of an object. *The Physics Teacher, 20*, 10-14.

Minstrell, J. (1992). Facets of student's knowlege and relevant instruction. In R. Duit, F. Goldberg & Niedderer (Eds.), *Research in Physics Learning: Theoretical Issues and Empirical Studies: Proceedings of an International Workshop* (pp. 110-128). Bremen, Germany.

Mullin, W. B. (1966a). The working of the Human Eye. *Physics Education, 1*(1), 34-38.

Mullin, W. B. (1966b). The working of the Human Eye II. *Physics Education, 1*(2), 104-106.

Mullin, W. B. (1966c). The working of the Human Eye III. *Physics Eduation, 1*(4), 276-278.

Nieswandt, M., & Bellomo, K. (2008). Written Extended-Response Questions as Assessment Tools for Meaningful Understanding of Evolutionary Theory. *Journal of Research in Science Teaching*.

Nieswandt, M., & Bellomo, K. (2009). Written Extended-Response Questions as Assessment Tools for Meaningful Understanding of Evolutionary Theory. *Journal of Research in Science Teaching, 43*(3), 333-356.

Nisbett, R. E., Fong, G. T., Lehman, D. R., & Cheng, P. W. (1987). Teaching Reasoning. *Science, 238*, 625-630.
Novick, L. (1988). Analogical transfer, problem similarity, adn expertise. *Journal of Experimental Psychology: Learning, Memory and Cognition, 14*, 510-520.
Parel, J.-M., Crock, G. W., & Perićič, L. J. (1980). The optics of the ophthalmoscope and related instruments. *Journal of Physics E: Science Instruments, 13*, 1242-1253.
Park, J. (2006). Modeling Analysis of Students' Process of Generating Scientific Explanatory Hypotheses. *International Journal of Science Education, 28*(5), 469-489.
Patton, M. Q. (1990). *Qualitative Evaluation and Research Methods*. Newbury Park, CA: Sage.
Perfetto, G., Bransford, J. D., & Franks, J. J. (1983). Constraints on access in a problem solving context. *Memory and Cognition, 11*, 12-31.
Phillips, D. C. (1995). The Good, the Bad, and the Ugly: The Many Faces of Constructivism. *Educational Researcher, 24*(7), 5-12.
Piaget, J. (1964). Development and Learning. *Journal of Research in Science Teaching, 2*(3), 176-186.
Posner, B., & Strike, K. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*, 211-227.
Rebello, N. S., Zollman, D. A., Allbaugh, A. R., Engelhardt, P. V., Gray, K. E., Hrepic, Z., et al. (2005). Dynamic Transfer: A Perspective from Physics Education. In H. P. Mestre (Ed.), *Transfer of Learning from a Modern Multidisciplinary Perspective*. Greenwich, CT: Information Age.
Redish, E. F. (1994). Implications of cognitive studies for teaching physics. *American Journal of Physics, 62*(9), 796.
Redish, E. F. (2003). *Teaching Physics with the Physics Suite*: Wiley.
Reed, S. K., Ernst, G. W., & Banergi, R. (1974). The role of analogy in transfer between similar problem states. *Cognitive Psychology, 6*, 436-450.
Ronen, M., & Eylong, B.-S. (1983). To see or not to see: the eye in geometrical optics - when and how? *Physics Education, 28*, 52-59.
Rozema, J. J., Van Dyck, D. E. M., & Tassignon, M.-J. (2005). Clinical comparison of 6 aberrometers. Part 1: Technical specifications. *Journal of Cataract and Refractive Surgery, 31*(June), 1114-1127.
Saxena, A. B. (1991). The understanding of the properties of light by students in India. *International Journal of Science Education, 13*, 283-289.
Schwartz, D., Bransford, J. D., & Sears, D. (2005). Efficiency and Innovation in Transfer. In H. P. Mestre (Ed.), *Transfer of Learning from a Modern Multidisciplinary Perspective*. Greewich, CT: Information Age.
Seidman, I. (1991). *Interviewing as qualitative research: A guide for researchers in education and the social sciences*. New York: Teachers College.
Springer, L., Stanne, M. E., & Donovan, S. S. (1999). Effects of Small-Group Learning on Undergraduates in Science, Mathematics, Engineering, and Technology. *Review of Educational Research, 69*, 21-51.
Stead, B. F., & Osborne, R. J. (1980). Exploring Students' Concepts of Light. *Australian Science Teacher's Journal, 26*(3), 84-90.
Stephenson, P., & Warwick, P. (2002). Using concept cartoons to support progression in students' understanding of light. *Physics Education, 37*(2), 135-141.

Strauss, A., & Corbin, J. (1990). *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*. Newbury Park: Sage.

Thibos, L. N. (2000). Principles of Hartmann-Shack Aberrometry. *Journal of Refractive Surgery, 16*(Sept/Oct), S563-S565.

Thibos, L. N., Applegate, R. A., Schwiegerling, J. T., & Webb, R. (2000). Standards for reporting the optical aberrations of eyes. In V. Laksminarayanan (Ed.), *Trends in Optics and Photonics* (Vol. 35, pp. 232-244). Washington D.C.: Optical Society of America.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*, 45-69.

Vosniadou, S. (2002). On the nature of naive physics. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice*. Dordrecht: Kluwer.

Vosniadou, S., & Brewer, W. (1992). Mental Models of the Earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*(535-585).

Vygotsky, L. S. (1978). *Mind in Society: The developemnt of Higher Psychological Processes*. Cambridge: Harvard University Press.

Watts, D. M. (1985). Student conceptions of light: A case study. *Physics Education, 20*, 183-187.

Wells, M., Hestenes, D., & Swackhamer, G. (1995). A modeling method for high school instruction. *American Journal of Physics, 63*(7), 606.

Wosilait, K., Heron, P. R. L., Shaffer, P. S., & McDermott, L. C. (1998). Development and assessment of a research-based tutorial on light and shadow. *American Journal of Physics, 66*, 906-913.

Appendix A - Interview Protocols

The following are the protocols used during each phase of this research project. They appear in chronological order, as used during the study.

KANSAS STATE UNIVERSITY

INFORMED CONSENT TEMPLATE

PROJECT TITLE: Modern Miracle Medical Machines

PRINCIPAL INVESTIGATOR: CO-INVESTIGATOR(S): Dean Zollman

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1 Fairchild, Kansas State University, Manhattan KS, 66506, (785) 532-3224

Jerry Jaax, Associate Vice Provost for Research Compliance
1 Fairchild, Kansas State University, Manhattan KS, 66506, (785) 532-3224

SPONSOR OF PROJECT: National Science Foundation

PURPOSE OF THE RESEARCH: To investigate students' understanding of the application of concepts in physics to contemporary medical diagnosis tools.

PROCEDURES OR METHODS TO BE USED: Interviews, written open-ended and multiple choice questions

ALTERNATIVE PROCEDURES OR TREATMENTS, IF ANY, THAT MIGHT BE ADVANTAGEOUS TO SUBJECT:

None

LENGTH OF STUDY: 30 - 120 min

RISKS ANTICIPATED: No known risks

BENEFITS ANTICIPATED: Deeper understanding of the application of physics to medicine

CONFIDENTIALITY: The student's performance and/or statements during interview and in survey will not be disclosed with students' name or any identifying feature.

PARENTAL APPROVAL FOR MINORS: Not Applicable

PARTICIPATION: Voluntary

I understand this project is for research and that my participation is completely voluntary, and that if I decide to participate in this study, I may withdraw my consent at any time, and stop participating at any time without explanation, penalty, or loss of benefits, or academic standing to which I may otherwise be entitled.

I also understand that my signature below indicates that I have read this consent form and willingly agree to participate in this study under the terms described, and that my signature acknowledges that I have received a signed and dated copy of this consent form.

Participant Name: ____

Participant Signature: ____ **Date:** ______________________

Witness to Signature: (project staff) ______________________________ **Date:** ______________________

- Thanks for coming. (Small talk). Background questions:
    - What physics courses have you taken so far – what year are you in?
    - Have you taken any classes in Optics?
        - Part of a course, or stand alone?
        - Geometric (lenses) or physical (interference)
        - Any "cool" experiments that stand out in your mind?
    - Have you done any optics things outside of class
        - Cameras, telescopes, etc

- So before we get started, I'd like to ask about your vision. (Note if they have glasses – if not, ask if they have contacts.)
    - Do you know why you have glasses/contacts?
    - What part of your vision do you have trouble with?
    - Does anyone else in your family (or anyone you know) have vision problems? (have them explain if possible)
- Can you please describe for me how the human eye works?
    - How does the eye relate to what you know about simple lenses? (only if interviewee does not bring it up on their own)

Bring models up 1 at a time, and then set aside before bringing in the next one. Don't show them how the models work this first time around, but carefully answer their questions if asked.

- Please take a look at this, and explain the features of the model to me.
    - How does this model help you understand how the eye works?
        - In what way(s)?
    - Are there any thing on this model that doesn't help (or even hurts) your understanding of how the eye works?
        - In what way(s)?
    - How do those helpful features compare to what you told me earlier about how the human eye works? (mention specific things they said if possible)

After all models have been talked about, bring them all back onto the table so that the interviewee can see them all to compare.

- Out of all the models we talked about, which model do you think does the best job in terms of representing what you said about how the eye works?
    - How was that model better than the others?
- In those terms, which of these models do you think did the worst job?
    - In what ways?
    - What could have been done to make it better?

Now go back to the models one at a time – in the same order as done above – and show the interviewee any features that they might have overlooked. Allow the interviewee to manipulate those features, and ask essentially the same questions.

- Now that you know a bit more about how the model works, are there any new features you can explain?
    - Does that feature change how the model fits with your description of how the eye works?
        - What made that feature more effective?

After all the models have been examined a second time, ask students to again look at them and compare using their new information.

- Now that you know a little bit more about how the models work, does it change which one you think best helps you understand how the eye works?
    - If yes, what features caused the change?
- Does it change which model fits in the least with how you know the eye works?
    - What makes it less effective than the others?
    - What could be done to make it more effective?

Now don't refer to any models, but ask the students some questions that they may not have brought up on their own.

- Why do people squint to see things that they can't otherwise?
    - How does it help?
    - Could any of these models demonstrate squinting?
- Do you know what accommodation is? Can you explain?
    - Do any of these models demonstrate it?
        - How?
- How about near-sightedness and far-sightedness?
    - Do any of these models demonstrate it?
        - How?
- What about astigmatism?
    - Do any of these models demonstrate it?
        - How?

Close the interview by asking students to describe what features their ideal model would include.

- If you could design your own model to represent how the eye works, what features would you include?
    - What features would be most important to your model?
        - What makes them necessary?
    - What features would be least important?
        - What makes them unimportant?

Phase 1b – Interviews
Measurement/Diagnosis

- Thanks for coming and small talk.
- IRB stuff: This interview is part of a research project to help us understand better how to teach introductory students. We will basically just discuss your ideas about some physics topics. However, we want you to know that your participation is entirely voluntary. If you feel uncomfortable at any time, you may stop the interview and leave. Also, you will not be identified in any way in any report about the research, and your physics instructor will not be told anything about the interview. The University requires that we tell you this and that we have you sign a statement that you understand the voluntary nature of the interview.

    (In case anyone asks, they do get paid even if they quit in the middle. However, I cannot remember anyone ever asking this or quitting.)

    I our discussion there are no right answers. To get the most useful information for our work, we need to know what you know and how you think about some topics in optics. So, just tell us what you know about a topic. As you are thinking about an answer, it is very helpful if you think aloud.

- Ask about what Optics they have learned again?
    - o What physics have you studied in high school and college?
    - o Have you learned any physics outside of formal classes?
        - If yes, what and how?
    - o Did you study optics in any of the classes?
        - If yes, tell me a little about what you have learned?

- I would like to show you this diagram. (Show eye chart).
- Do you know what it is?
- Okay, let's think about the physics of light for a little bit. What is going on that allows you to see this chart?
    - o May need to do some prompting here to get them on the right track. E.g.
        - If we turned off the lights in this room, we could not see the chart. How does the light from the overhead lights travel and interact to allow us to see the chart?
- What about your glasses (or contacts, or my glasses)?
    - o How would the chart look to you/me if you took off your/my glasses/removed your contacts?
    - o What do they do to allow you to see this chart better?

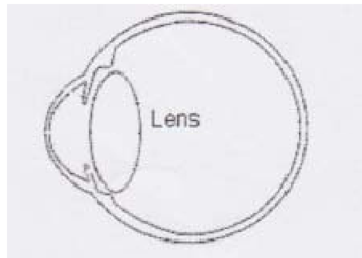
- Here is a model of the eye. (start with light coming INTO the eye)
    - o What about this model relates to what you said about how you see the chart?

- Let's think now about an eye exam.

- When you go to a doctor, how does he or she use that chart to determine how good your eyesight is?
    - What do you think are the benefits of using a chart like this?
    - Can you think of any negatives for using a chart like this?
        - "Did you ever have trouble telling the doctor whether on lens was better than the other?"

- I'd like to tell you about another method that is used for diagnosis.
    - Have you ever heard the term "aberration"?
    - Any idea what it could mean?
        - If not, tell them.

- Aberrometer measures aberrations in the eye. We can model an Aberrometer by doing something like this (Set up the LED and the lens array with a good lens). This lens is a perfect lens – it has very little or no aberrations in it.
    - What do you think is happening here?
    - Can you explain why the pattern looks like that (grid)?
    - What do you think would happen if the lens were not perfect, or if it had aberrations?
        - Here is an aberrated lens. Let's give it a try.
        - What happened to the pattern?
            - Can you explain the changes?
        - I want to show you this picture. (Figure from German paper)
            - What do you think this is illustrating?
    - A new way of testing vision is to have light in this type of grid pattern enter the eye and look at the light which comes back out. In this way the doctor (with the help of a computer) can see problems if they exist in the lens. It works just like the system which just talked about.
    - Now, suppose the lens were OK but the eyeball had a shape that was different from "perfect", would that cause any changes in the pattern?
        - If yes, in general terms what would you expect?
        - If no or I don't know, would the light reflecting off a surface change if the shape of the surface changes?
    - How do you think this helps a doctor to understand the aberrations in your eye?
        - What do you think are the benefits of using a method like this?
        - Can you think of any negatives for using a method like this?
    - Thanks this information will help us design some new teaching materials. Do you have any questions about what we have discussed or about how this research is done?
    - Small talk end.



The cross section diagram above shows some basic components of the human eye. The questions which follow refer to the eye's natural lens, labeled "Lens" in the diagram.

1. As shown above, the eye can see clearly objects which are about 2 meters away.
   a. Would the Lens need to change if the object moves to 6 meters away?

   b. If the answer to a is yes, how would it need to change? If the answer is no, go to part c.

   c. Explain your answers to parts a and b.

2. Now the object moves to 0.5 meters away.
   a. Would the Lens 'need to change to see this object?

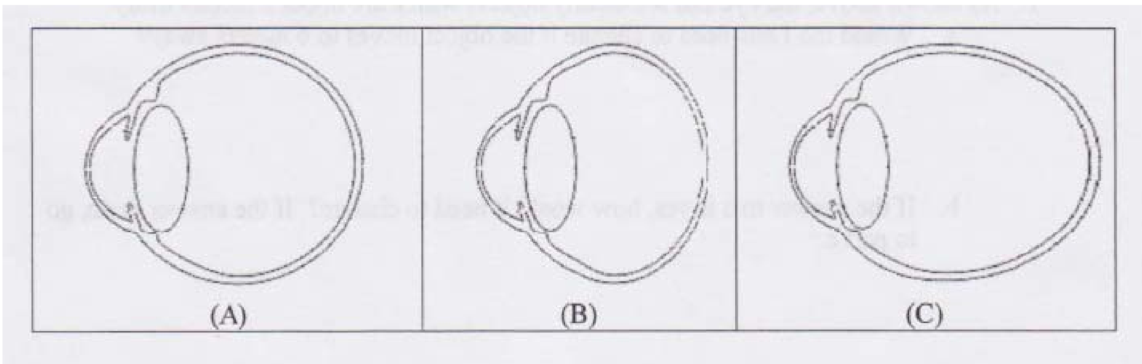
   b. If the answer to a is yes, how would it need to change? If the answer is no, go to part c.

   c. Explain your answers to parts a and b.

Drawings modified from Wikipedia

3. Can the Lens in the eye change its shape? If yes, explain how these how changes occurs. If no, explain why it is not necessary.

4. The diagrams below show a normal eye (A) and eyes with vision problems (B) and (C). Describe the type of lenses needed to correct the vision problems in eyes (B) and (C). Explain your answers.



- Thanks for coming and small talk.

- Let's continue talking about the eye. However today will be a bit different from last time, in that we'll do a lot more talking. In our discussion there are no right or wrong answers. To get the most useful information for our work, we need to know what you know and how you think about some topics in optics. So, just tell us what you know and think about a topic. As you are thinking about an answer, it is very helpful if you think aloud. Don't be afraid to tell me whatever comes to your mind.

- I would like to show you this diagram. (Show eye chart).
    - Do you know what it is?
- Let's think now about an eye exam. When you go to a doctor, how does he or she use that chart to determine how good your eyesight is?
- Have you ever tried to squint to see better? What does squinting do?
    - What do you think are the benefits of using a chart like this?
    - Can you think of any negatives for using a chart like this?
        - What about guessing at a letter you don't know?
    - Would you describe this method as subjective or objective?
        - Why? Definitions?

- I'd like to tell you about another method that is used for diagnosis.
    - Have you ever heard the term "aberration"?
    - Any idea what it could mean?
        - If not, tell them.

- Aberrometer measures aberrations in the eye. We can model an Aberrometer by doing something like this (Set up the LED and the lens array with a good lens). This lens is a perfect lens – it has very little or no aberrations in it.
    - What do you think is happening here?
        - How is light traveling through this system?
        - What about the lenses?
    - Can you explain why the pattern looks like that (grid)?
    - What do you think would happen if the lens were not perfect, or if it had aberrations?
        - Let's give it a try. Aberrate that lens by pushing on it.
        - What happened to the pattern?
            - Can you explain the changes?

- A new way of testing vision is to have light in this type of grid pattern enter the eye and look at the light which comes back out. In this way the doctor (with the help of a computer) can see problems if they exist in the lens. It works just like the system which just talked about.

        - Now, suppose the lens were OK but the eyeball had a shape that was different from “perfect”, would that cause any changes in the pattern?
            - If yes, in general terms what would you expect?
        - If no or I don’t know, would the light reflecting off a surface change if the shape of the surface changes?
            - Bouncing off a flat versus round surface?
    - How do you think this helps a doctor to understand the aberrations in your eye?
        - What do you think are the benefits of using a method like this?
        - Can you think of any negatives for using a method like this?
        - Would you describe this method as being subjective or objective?
            - Why? Definitions?

- Thanks. This information will help us design some new teaching materials. Do you have any questions about what we have discussed or about how this research is done?
- Small talk end.

- Thanks for coming and small talk. Introductions for myself and groups.

- Well, I heard that you guys have already talked about some optics in your GP2 class – some things about lenses and the eye. Well, what I'd like to do is show you this model of the eye that I have. What can you tell me about this model – is there anything that you recognize?
    - Make sure they identify all features:
        - Nearsighted/farsighted
        - Lens – accommodation
    - Okay, great. Well we'll come back to this model in just a few minutes. But first, I'd like to talk about something a little different.

- I would like to show you this diagram. (Show eye chart).
    - Do you know what it is?
- Let's think now about an eye exam. When you go to a doctor, how does he or she use that chart to determine how good your eyesight is?
    - What do you think are the benefits of using a chart like this?
    - Can you think of any negatives for using a chart like this?
        - What about guessing at a letter you don't know?
    - Would you describe this method as subjective or objective?
        - Why? Definitions?

- Have you ever tried to squint to see better? What does squinting do? How does it help us to see better?
- I'd like to tell you about another method that is used for diagnosis.
    - Have you ever heard the term "aberration"?
        - Any idea what it could mean? If not, tell them.

- Aberrometer measures aberrations in the eye. So let's go back to that eye model that we talked about. We can model an Aberrometer by doing something like this (Set up the LED and the lens array with a good lens).
    - What do you think is happening here?
        - How is light traveling through this system?
        - What about the lenses?
    - Can you explain why the pattern looks like that (grid)?

- Let's suppose the lens were OK but the eyeball had a shape that was different from "perfect", would that cause any changes in the pattern?
    - What would you expect?
    - Try it – how can you explain what did happen?

- What do you think would happen if the lens were not perfect, or if it had aberrations?
    - Let's give it a try. Aberrate that lens by pushing on it.
    - What happened to the pattern?
        - Can you explain the changes?

- Could you please draw something for me? What happens to light as it hits a lens at normal incidence
    - Now what about if it comes in from any angle other than normal?

- Now I'd like to show you a computer simulation that shows you a little more about the aberrometer.
    - What do you see happening?
        - Does it correspond to what we saw with the model of the eye?

- How do you think this helps a doctor to understand the aberrations in your eye?
    - What do you think are the benefits of using a method like this?
    - Can you think of any negatives for using a method like this?
    - Would you describe this method as being subjective or objective?
        - Why? Definitions?

- If you didn't know the definitions before, let's go back and talk about what they might mean …
    - Change answers for subject/objective for the eye chart? Aberrometer?

- Thanks. This information will help us design some new teaching materials. Do you have any questions about what we have discussed or about how this research is done?

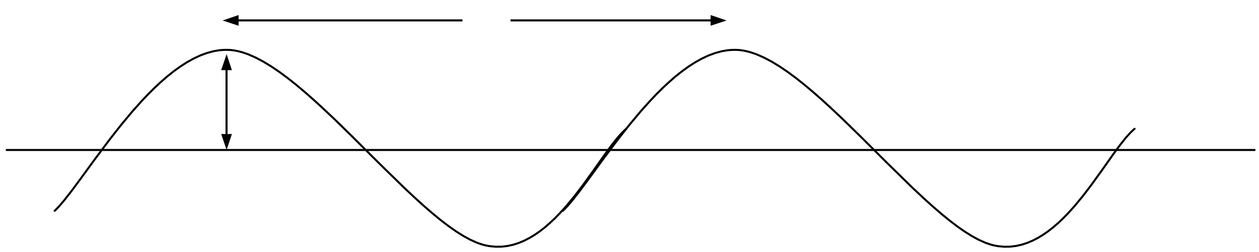
The Human Eye and Vision

Our most important sense organ is the eye; in general we receive more than 80% of our information about our environment from seeing. Thus, for us "proper" seeing is of utmost importance.

For us to be able to see an object, light reflected or generated from that object must enter our eyes. That means that the surface of the object must be stimulated to emit light. This could happen with a lamp, candle, the sun, or other sources in which the object is raised to a high temperature and the atomic particles vibrate and thereby emit electromagnetic waves. Light is an electromagnetic wave. The light which enters the eye is converted by the retina into electrical impulses. These signals are transmitted to the brain where they are analyzed and interpreted.

A Quick Review of Waves

As we said earlier, light is an electromagnetic wave. Because it is an electromagnetic wave, light is self-propagating – it does not need a medium. A basic wave can be seen below. The amplitude (A) and wavelength (λ) of light are both very important characteristics – they are illustrated on the simple drawing below. The wavelength of light is what determines the colour we see, and the amplitude determines how bright the light is.



Modeling the Eye as an Optical System

In this section, we will look at ways to create models of the eye. As with many models in science, we will start with a relatively simple one and then build upon it to better match reality. Along the way, we will find that some animals in nature have evolved to have eyes that are similar to each of the models. These eyes can be very different, but they have one thing in common: eyes in all animals are approximately a sphere which collects light, and the light falls on a detector which converts the light into signals which are sent to the brain to be interpreted.

We can use some simple optics equipment on an optical table or optical rail to model the eye. Though it will not "look like" an eye, it will function in much the same way. First, mount a screen on one side of the optics table – this represents the *retina*, or the place where the image falls and is converted into electrical signals in the real eye. For our purposes, we will just observe images on this "retina" to see how they would appear before being converted. On the other side of the table, mount a light and shine it toward the screen. This will serve as the light that shines into the eye.

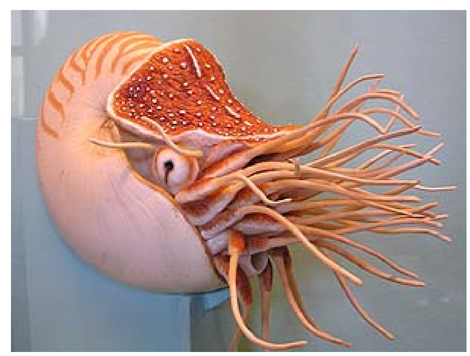
The Simplest Eye

♦ For the first model, mount an adjustable "iris" approximately 17cm in front of the retina (screen). The hole that is in the center is known as the *pupil*. Adjust the iris so that the pupil is as large as possible.

? Describe the light you see on the retina.

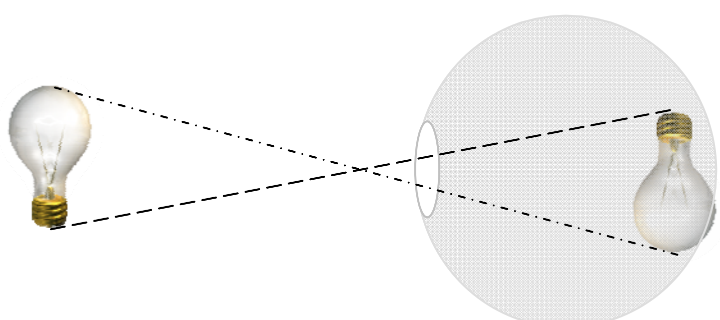
As you can see, the light which reaches the retina in this case is not an image but just a spot of light.

♦? To create the first image, make the pupil as small as possible (about the size of a pin-hole). Describe what you see.



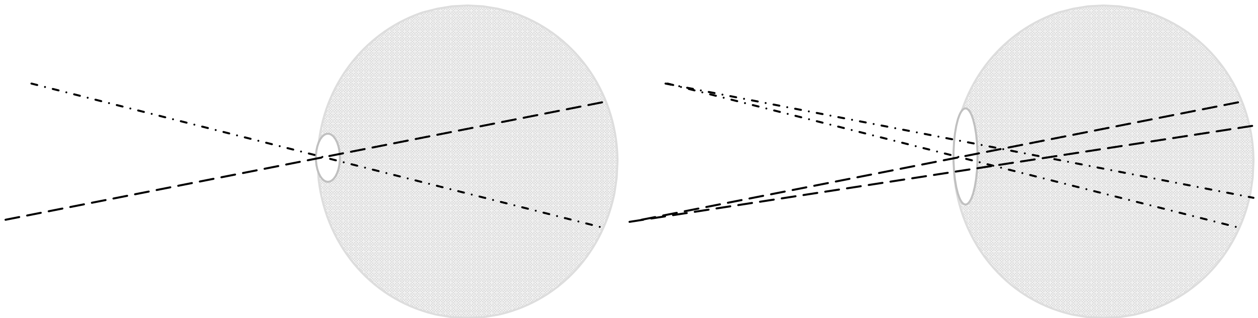
An eye similar to this model is called a pinhole eye. This type of eye is the simplest of all eyes, and exists in some sea animals such as the cephalopod called the Nautilus. (Image from http://www.weichtiere.at/Kopffuesser/nautilus.html) The eye is the circular object located in the center of the image.

The origin of the image created by the nautilus' eye is relatively easy to understand. A ray of light goes straight through the small opening and creates a point of light on the retina. The figure below shows two such points representing the surface. From this representation, we can see immediately that the image is both inverted (upside down) and reversed. These images are also made by pinhole cameras.



♦? Now vary the size of the opening in the iris and describe how the image changes.

As you saw in the experiment, the image in a pinhole camera or eye is very faint. In order to make it brighter, we must increase the size of the opening. Then, the light rays are not so constrained in their paths. However the images from different sets of rays overlap, and so the image becomes less sharp, as seen in the figure below. So, the smaller the pinhole is, the dimmer but sharper the image is.



Pinhole eyes work well for animals that only need limited vision. However, the limitations we saw above make it inadequate for humans.

For an image that is both bright *and* sharply focused, we must have a somewhat large opening. As light passes through this opening, the light rays need to be gathered in such a way that they create a sharply focused image.

A more complex (and realistic) eye model

To obtain both a large opening and focusing, we require a lens, which most animal and human eyes have. Thus, to improve our model, we need to add lenses.

♦ First, re-adjust the pupil so that it is again as large as it can be. Just behind the pupil, mount a convex lens.

? Describe the image on the retina.

? To see how the eye works at different distances, move the light source either closer to or farther from the retina. Describe how the image changes with distance.

How a converging lens creates an image

♦ To explore image creation with lenses, start the "Optik" simulation, and choose "Light Rays Through Lenses." To investigate what happens with light, we have selected only two points. Light from these points goes in all possible directions. However, only two light rays which fall on the lens are represented. (Of course, the light traveling away in other directions can contribute nothing to the image formed on the retina). The lens changes the light direction in such a way that the light gathers behind the lens. If we place a screen (with the eye this would be the retina) at the proper locations, then we observe on the screen both images of the object. If we shift the screen, the points become indistinct or blurry. In order to have a sharp image, we can either shift the screen or use a different lens.

♦? Explore with the computer simulation by placing the object at different distances away from the lens, and attempting to get them in focus by moving the screen. Is it possible to focus on object very near to the lens? Very far from the lens?

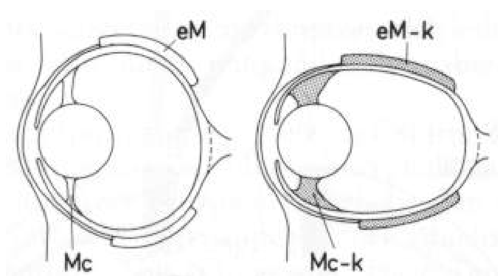
? The place where the image can be clearly seen is called the focal point of a lens. What factors determine where the focal point of a lens will be?

Accommodation – varying the range of vision

As you can see, the converging lens improves the light gathering ability of the eye and can create sharp images on the retina. However, as you see in the model and the simulation, one lens is not sufficient for seeing objects at a broad range of distances. Somehow the eye must change (accommodate) to allow us and other animals to view objects at different distances.

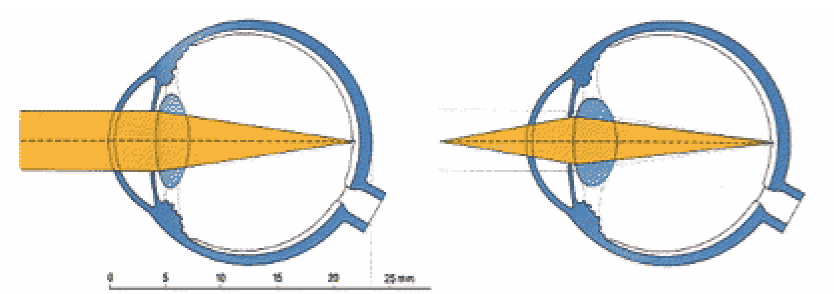
♦ To see one way in which accommodation occurs, you can use the simulation. Click on the arrow in the bottom right corner of the screen to go back to the main menu. This time, chose "Light Rays in the Eye." Set the object at some small distance from the eye. Then, adjust the lens inside the eye so that the object focuses sharply on the retina. Now move the object slightly so that the image is slightly less than sharp. To bring it back to sharp, move the back of the eye.

As you can see, changing the distance between the lens and the retina can help change the focus of the image. This type of accommodation occurs in some sea animals such as sharks and squid. In this photo from Horn (1982), we can see the eye of a squid with both the relaxed (for average distances) and contracted (for shorter distances) positions of extra-ocular (eM) muscle.

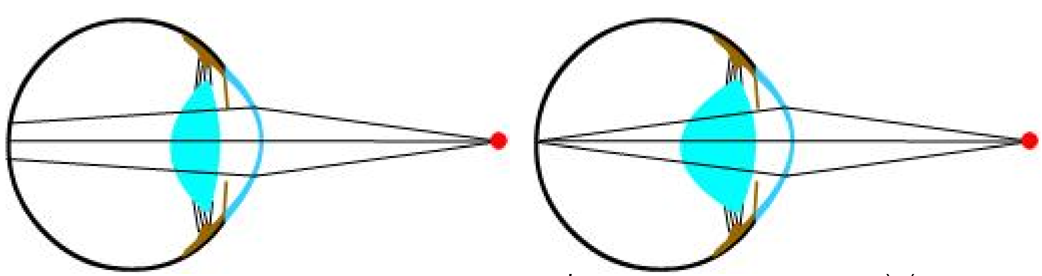


♦? The human eye adapts so that we can see objects at different distance in a different way. Our eye does not change shape like in the previous examples. To see how our eye accommodates, go back to the simulation. Make sure that the “automatic focusing” option is turned off, and hit the “Normal” button to return the shape of the eye to normal. Now change the thickness of the lens a few times. For each thickness, move the object and record your observations about the image. What do you notice about the thickness when the objects are close to the eye? What do you notice when the objects are far from the eye?

As you can see from the simulation, the lens of the human eye needs to change in order to accommodate for objects at different distances. If the lens is made thinner than average in the center, the location of the object for which the image is clear moves away from the eye. If the lens is thickened in the center, the object location for a clear image shifts toward the lens. This remarkable property of the lens to bring together diverging light rays is called its refractive power. With a lens of high refractive power, the object near the lens is clear; with smaller refractive power it is further away.



The pictures on the left show a representation the eye accommodating for distance vision; on the right is accommodation for close vision.
(http://www.augen.de/index.php?id=info_fehlsichtigkeit)



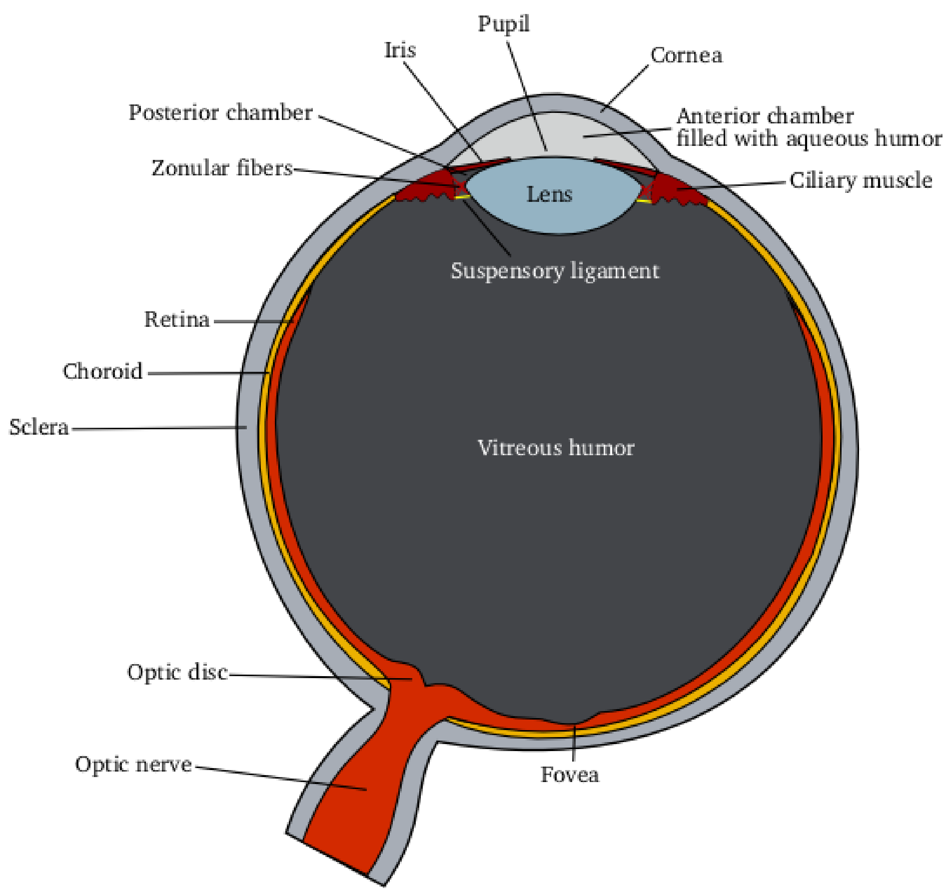
Viewing an
without accommodation of the eye lens and (b) with accommodation. (http://www.blue-eye-divers.ch/index.php?page=10.20)

As the simulations show, we need a lens in our model so that it represents the human eye. In fact, we need to add a lens that can change its shape. This lens is located slightly behind the fixed lens that you have already installed. By changing its thickness, the eye lens enables us to see objects at a vast range of distances.

Anatomy of the Eye

Let's pause for a moment and look at the anatomy of the eye. The human eye is approximately a sphere with an average radius of about 24 mm. It consists of the following parts

- the cornea, which is scarcely a millimeter thick, has no blood supply of its own and is completely transparent
- the eye chamber, which contains a liquid (aqueous humor)
- the iris, which has a circular hole (pupil) at the center and is the “eye color”
- the flexible accommodating lens, which is attached by a elastic ring of ligaments called the zonula to the ciliary muscle
- the vitreous humour, which fills out the eyeball volume
- the retina, which lines the rear internal surface of the eye and is where the image falls in the eye



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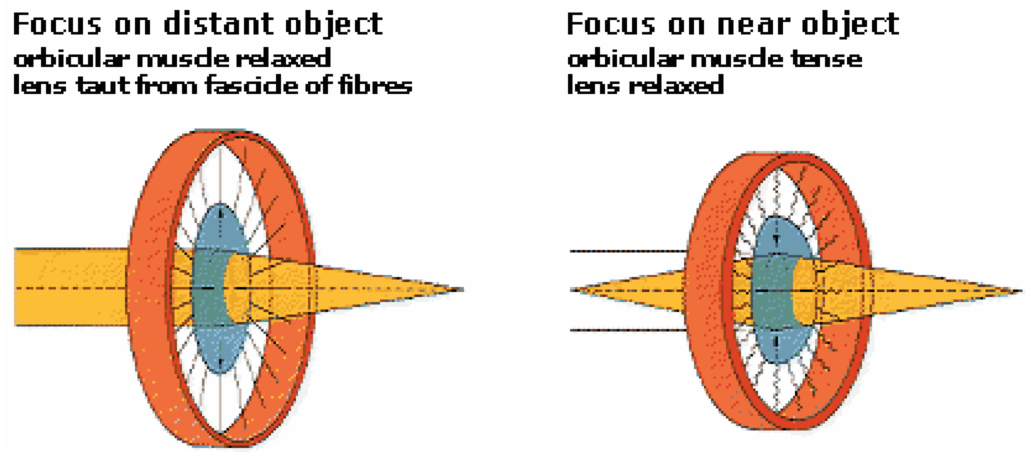
From: http://en.wikipedia.org/wiki/Eye & http://de.wikipedia.org/wiki/Auge

The visible light must go through the optical apparatus of the eye to be able to stimulate the retina. Just like we saw when using the computer simulation and the eye model, the refracting power can be changed in two ways:

1. by the muscles outside of the eye deforming the whole eye ball, including the cornea, or
2. by the ciliary muscles changing the curvatures of the lenses (accommodation).



Accommodation: When the ciliary muscles are relaxed the lens becomes thin for looking at distant objects. By becoming tense the muscles cause the lens to become thicker to view close objects. Adapted from www.augen.de/uploads/RTEmagicC_4c78fee701.gif

Vision Defects

Most of us have or will have some vision problems. These difficulties in seeing may be minor inconveniences or major short comings in our ability to see clearly. They may appear early or late in our lives. Fortunately, many methods from eye glasses and contact lenses to surgery are available to make corrections to our natural optical (ocular) system. However, before eye specialists can make corrections they must know very precisely what the problem is. Most eye defects are limited to three common problems – nearsightedness, farsightedness and astigmatism. We can use the simulation or the eye model to understand the physics behind these vision defects.

Exploring vision defects with the eye model

♦? To create an eye model with a vision defect, move the retina (the screen) so that is farther away from the fixed lens. Make sure that the accommodating lens is about average thickness – not too thick or too thin. Again move the light source closer and farther to explore how the eye works for different distances. Record the results below by stating the approximate distance from the eye and the quality of the image on the model retina. For image quality you may use phrases such as "sharp", "slightly blurred", and "very blurred".

♦? Repeat the experiment recording the distance and image quality, this time with a shorter distance from the lens to the retina.

Exploring vision defects with computer simulations

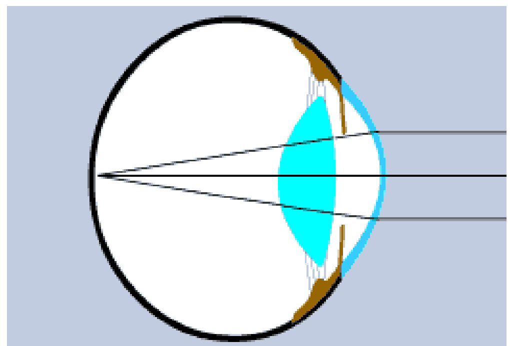
The computer eye model allows you to move the location of the retina and, thus, create an eye model with a vision defect. You create the vision difficulties by moving the retina.

♦? First, move the retina to the location farthest from the lens. Now move the objects so that they are many different distances from eye. Record the results below by stating the distance from the eye and the quality of the image on the model retina. For image quality you may use phrases such as "sharp", "slightly blurred", and "very blurred". Also, make note of where the focal point is in relation to the retina (e.g. behind or in front).

♦? Now, move the retina to the position that is close to the lens. Repeat the experiment recording the distance and image quality and focal point location.

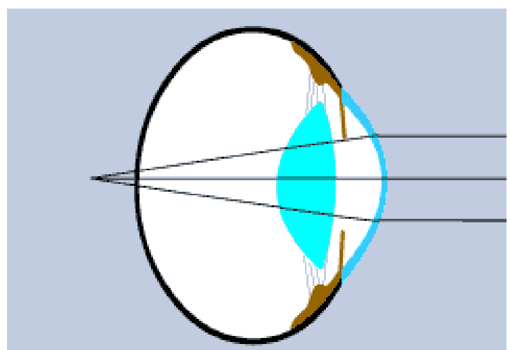
? From your experiences with the model and simulation, how would you describe nearsightedness and farsightedness and what causes each of them?

Explaining Vision Defects



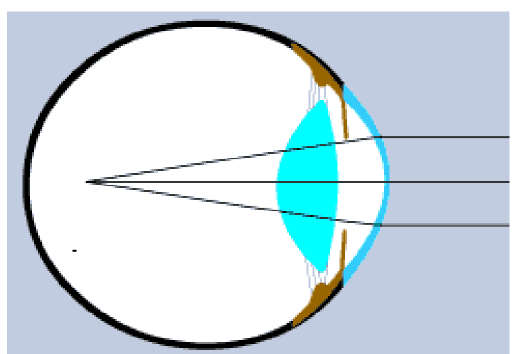
The explorations indicated that common vision problems arise because the eye ball is either longer or shorter than normal. As a result we can see objects in a limited range of the distances that we would like to see. A perfect eye – one with no vision defects – is one that is very spherical in shape. However, as you saw with the model and the computer simulation, when the eye is shaped even slightly different, our vision changes drastically.

Hyperopia (Farsightedness)



As you saw, in this situation the eyeball is abnormally short or has a lens with a lower refracting power than normal. The result is that the focal point lies behind the retina. The light that reaches the retina is not focused there, and so the image is blurred. In this case the eye is better able to see distant objects because these objects focus close to the retina. The name farsighted comes from this observation.

Myopia (Nearsightedness)



As you saw, the eye that is longer than normal has better vision for objects that are near to it than for ones that are far away. This type of defect is called nearsightedness or myopia. In this case, the image focuses in front of the retina, and so the image on the retina is blurry.

For objects that are close to the eye, this condition is pronounced. Thus, when a person with myopia looks at very near objects, he/she sees somewhat clearly, and hence this condition is given the name nearsightedness.

Photos from http://www.blue-eye-divers.ch/index.php?page=10.20

Astigmatism

Astigmatism, which we have not explored yet, occurs when the cornea does not have a spherical shape. In most cases, the curvature in one direction is different from the curvature in another. The shape of the cornea in an astigmatic eye is likely to be similar in shape to an American football or a rugby ball rather than a European football (soccer ball) or a basketball.

The result of the different curvatures is that the eye has more than one place where the image focuses. Because of the lack of symmetry in the lens, a person with astigmatism cannot see any objects clearly. This condition is frequently accompanied by one of the other eye conditions.

Other Defects

Many other conditions can cause vision difficulties. However, these three are the ones that are most closely related to the optical properties of the eye. For a rather complete list of eye conditions see http://www.stlukeseye.com/Conditions/Default.asp. Many graphical representations of eye defects are also available on the web, for example see http://www.tehranlasik.com/diseases/mupia%20.htm and www.eyeny.com/eye/index.shtml

Accommodation and Vision Defects

Accommodation also plays a role in vision defects and can help us partially adjust to abnormal vision. To see how this attribute improves our vision, even with less-than-perfect vision we will do some experiments with the model of the eye and a lens that can vary its thickness. The lens on our model varies through the addition of water through a syringe. As we discussed above, this process is *not* the way our eye works, but it provides a simple working model and demonstrates the principle.

♦? First, we will see how the adjustable lens models accommodation. Start with a thin lens, a normal-shaped eye, and the light source in focus. Move the light source until it is no longer in focus on the retina. Then, adjust the thickness of the lens until the object comes back into focus. Describe what you changed and how that change affected the image. Explain where the focal point of the image was in comparison with the retina of the eye.

? Repeat this process with a nearsighted and farsighted eye. In each case, describe the range over which you can keep an object in focus:

Nearsighted eye

Farsighted eye

Optical Corrections for vision defects

Hyperopia (Farsightedness)

♦? Set the simulation for a farsighted eye. If you have forgotten what change to make, refer back to the discussion of eye defects. As you know, a corrective lens such as eye glasses or contact lens sit in front of the eye. This lens must do something to cause the light to focus on the retina. Just by looking at the model and the simulation, describe how the lens must change the light so the focus is on the retina.

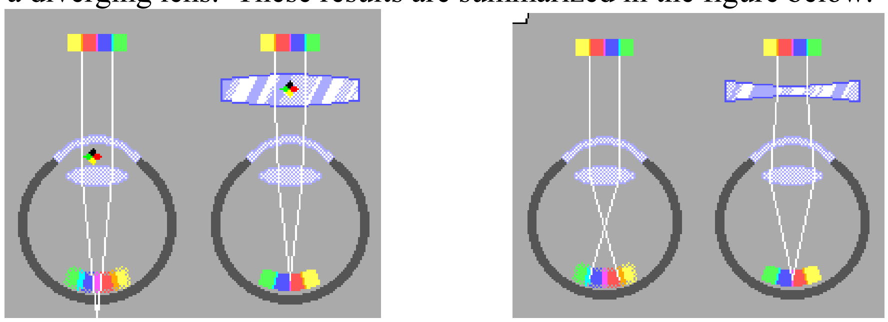
♦? Try to make the corrections for the simulation. Describe the results and the properties of the lenses that work.

Myopia (Nearsightedness)

♦? Now set the simulation for nearsightedness. Predict what the lens will need to do to create an in-focus image on the retina.

♦? Try the simulation. Describe how the corrective lens is different from the one in the case of farsightedness.

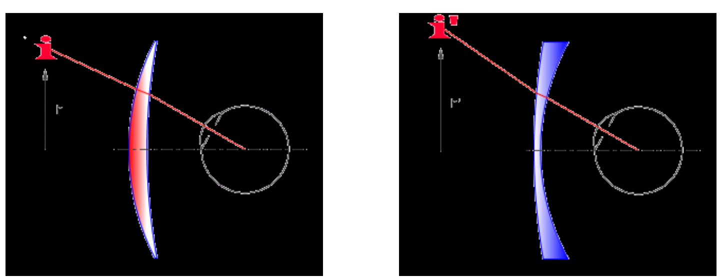
In the case of farsightedness we needed to cause the light to focus a shorter distance than usual. Then, the image would appear on a retina which is closer to the lens than normal. This type of lens is called a converging lens. As its name implies, it causes the light to converge and focus. For nearsightedness we needed a lens that caused the light to diverge a little and focus in a longer distance than normal. Thus the lens that you used was a diverging lens. These results are summarized in the figure below.



(http://www.innerbody.com/image/nerv10.html)

As you saw from the simulation with lenses, the converging lens is thicker in the middle than it is on the edges, while the diverging lens is thicker on the edges. You can learn more about why these types of lenses work if you study more about optics.

You may be thinking that the lens that we used to diverge the light rays was somewhat different from any you have seen in eye glasses – even your grandfather's glasses. And, it is. Our lens is the simplest form of a diverging lens. It works for objects that are straight in front of it only. For real glasses the lens itself needs to curve so that the optical corrections work when we look at objects off to the side. The drawings in Figure 9 show the shapes of typical converging and diverging lenses for eye glasses. The lenses for a nearsighted eye are thinner in the middle, but that shape is more difficult to notice because of the curved shape of the lens. If you want to manipulate some of the properties in these lenses, try: http://thierry.baudart.waika9.com/unifocal/doc/index.htm



http://thierry.baudart.waika9.com/unifocal/doc/index.htm)

Beyond Lenses …

Corrective lenses were apparently first used sometime around the year 1200. By the middle 1300s eye glasses that sit on the noses of the users were appearing in paintings. Developments in various types of frames and in the quality and materials of the lenses have continued for the last 800 plus years. However, even with the advent of contact lenses the basic solution to vision problems has remained the same – put a corrective lens in front of the eye. Both the corrective procedures and the methods for determining those corrections are changing rapidly at this time. Surgery to make corrections to eye defects, primarily by changing the shape of the cornea, is still somewhat controversial but is also rather common. Next time, we will talk more about these new techniques.

WAVEFRONT ABERROMETRY

By now, you know quite a bit about the human eye and how it functions, as well as some information about vision defects such as nearsightedness and farsightedness. In the next section, we will explore some ways in which we can diagnose these vision defects.

The Model of the Eye

? In front of you is the same equipment that we used in the past two labs to model the human eye. What features of the model do you recognize?

? How does one account for nearsightedness and farsightedness in this model?

? What about the accommodating lens? How does it work in this model?

Vision Diagnosis

? Here is a picture of a typical eye chart that is used at a doctor's office. How does an eye doctor use a vision chart like this one to diagnoses vision defects?

? What are the advantages of a system like this one?

? What are the disadvantages of a system like this one?

? Have you ever tried to squint to see one of the letters (or anything else) better? What does squinting do to help us? Why does it help?

Modeling the Aberrometers

Now let's look at a new method that's being used for vision diagnosis. It is called an aberrometer – it measures the aberrations (or differences from the normal) in our eyes. Aberrations are like defects, and they can occur in any part of our vision system.

♦ We're going to make a model of an aberrometer by using the eye model we've been looking at. In the real aberrometer, a light source comes into your eye, reflects off the retina, and comes back out through the front of the eye. This would be rather hard to imitate, so we'll make it simpler: take the small flashlight and clip it to the "retina" so that it points out through the front of the eye. Next, we need a screen so that we can see the light – put up the grid paper screen so that it's just in front of the eye. Lastly, there is an array of small lenses that is the essence of the aberrometer.

? You have a lens array sitting right in front of you – one of the lenses is loose – take it out and look at it. What kind of lens is it? How do you know?

? What does that type of lens do with the light?

♦?	Now place the array in the slot in front of the eye – what do you see on the screen?

?	Why do you see it?

The grid pattern that you described above is where we will focus our attention for the rest of this activity.

Nearsightedness and Farsightedness

♦?	Right now, the eyeball is set up in such a way that there are no aberrations (defects) in the eye or its components. What do you think would happen if, instead of a perfectly shaped eye, we had an eye that was either longer or shorter than normal? What would happen to our grid pattern, and **why**? (Hint – what is happening to the light?)

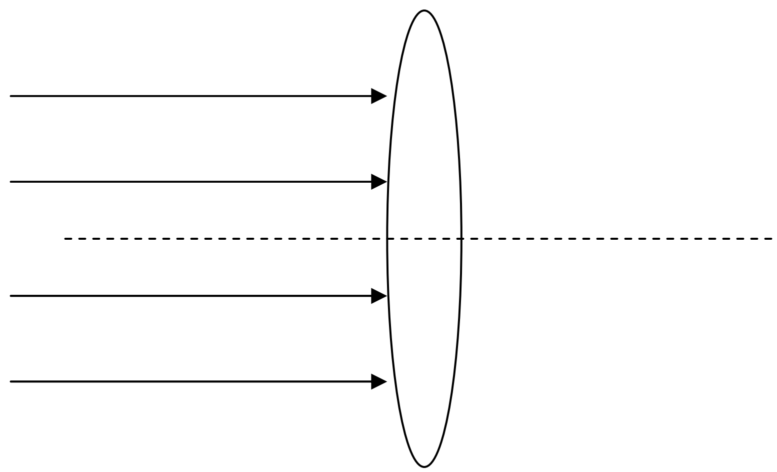
♦? Go ahead and try it out. Change the shape of the eye (while keeping the flashlight aimed at the lens), and see what happens to the grid pattern. What changes are happening? Why? Does it agree with what you predicted above?

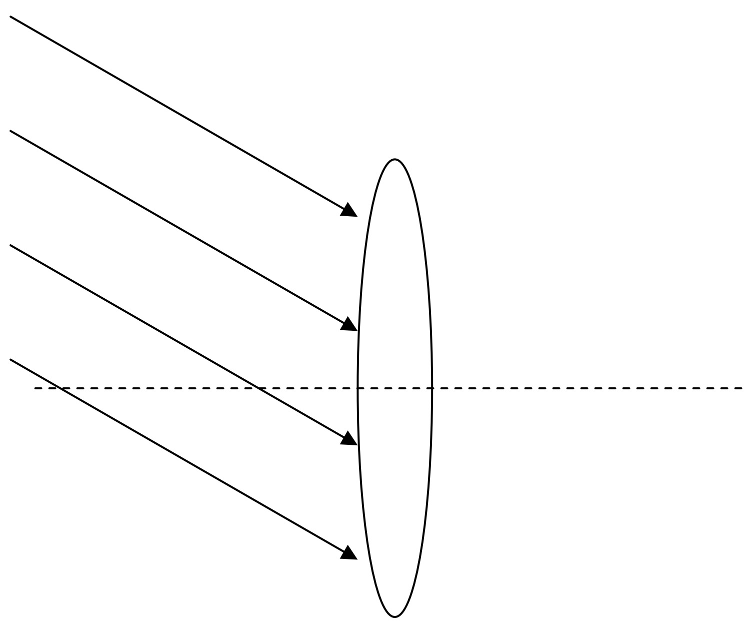
Aberrations in the Lens

♦? Now make sure the eye is back to a normal shape. This time, please predict what you think would happen if the lens of the eye had an aberration – if it was not as well shaped like it is right now. What do you think would happen to the grid pattern, and **why**?

♦? Try it – the lens is flexible, so just reach in and push on it lightly. What do you see happening? Why? Does it correspond to what you predicted above?

? Below are two lenses (both are identical), with light rays entering as shown. Please draw the light rays on the other side, after they passed through the lens. If they make a focal point, mark it with a dot.





? Does the above exercise help you to explain what you saw with the grid pattern? If so, how does it help? If not, then why didn't it?

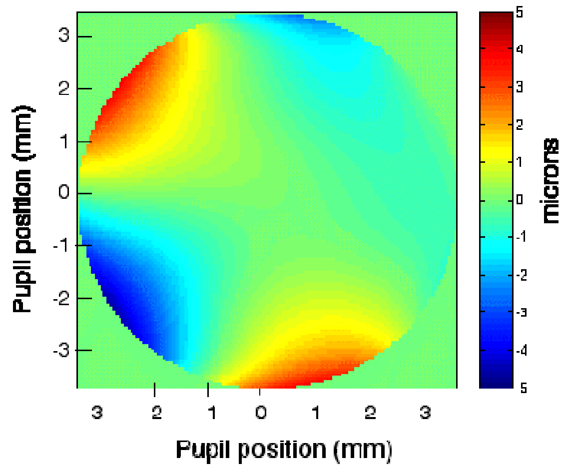
♦? Now let's look at a computer simulation that shows you a little bit more about the aberrometer. It's called the "Shack" program – load it up, and switch to English. The white diamonds allow you to change the eye. Move both of them – one allows you to change the length of the eye, and the other allows you to deform the front of the eye. Does this simulation correspond to what you saw with the model? How are the model and the simulation similar?

? How do you think that a doctor could use a system like this aberrometer to diagnose vision defects, both near/farsightedness and aberrations?

? What do you think are some advantages of using a system like this one?

? What about any disadvantages of using a system like this one?

Conclusion



This is actually quite like a real aberrometer. The "screen" is actually a highly sensitive detector that can measure properties of the grid pattern of light that fall on the screen – it measures position, intensity, size, etc of the dots of light – the very things you saw changing with the defects. That information is then taken by a computer program and, by using some mathematical algorithms, turned into what looks like a map of the defects of your eye, like in the picture seen here. This type of diagnosis tool is frequently used in conjunction with laser eye surgery techniques, and is very quickly gaining popularity.

? In the space below, please write a short summary of what you learned from this activity, and how it relates to what you learned in your class lecture and lab.