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Year 12 Students' Understandings of Models within the Context of Learning Optics

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Abstract

This paper will report on the third year of a three-year longitudinal investigation into six secondary students' understanding of optics at a secondary school level. During the first two years of the study the students' understanding of geometrical optics was explored with the adoption of constructivist teaching and learning strategies. The researcher acted in the dual roles of teacher and researcher. The students' understanding of geometrical optics following the Year 11 teaching stage then formed the basis of exploration of their mental models of the nature of light in addition to their understandings of the nature and function of scientific models. This exploration occurred before, during, and following a Year 12 teaching stage where the students studied physical optics and quantum ideas. This paper will outline the findings of the third year of this study with respect to the Year 12 students' understandings of the nature and function of scientific models and the linkage between these understandings and the students' mental models of light.

Introduction

Driver, et al (1994, p. 5) assert that "the objects of science are not the phenomena of nature but constructs advanced by the scientific community to interpret nature". Individuals have devised these constructs as they attempt to make sense of their experiences and are then shared and negotiated with the scientific community until a consensus view is reached (Guba & Lincoln, 1991). The social dimension of the construction of scientific knowledge has led to the scientific community sharing a view of the world involving concepts, models, conventions and procedures (Driver, 1995).

The concepts of science represent the socially negotiated meanings given to terms or processes constructed by individuals to interpret their interactions with the physical world. The models of science are representations of objects, events, ideas, systems or processes (Gilbert, 1995). Scientific models are one of the main products of science (Halloum, 1996; Gilbert, 1994) and play a crucial role in reducing the complexity of phenomena by allowing a more visual reproduction of abstract theories so that predictions of behaviour can be made and tested (Gilbert, 1995). This view is supported by Gilbert and Boulter (1995a) who have suggested that the role of the scientific model in science should be seen as "an intermediary between the abstractions of theory and the concrete actions of experiment, helping to make predictions, to guide enquiry, to summarise data, to justify outcomes, and to facilitate communication" (p. 3). Grosslight, Unger, Jay and Smith (1991) suggest that there is a clear distinction between the scientific model, reality and ideas or concepts about reality. The model is in the service of the ideas and ideas are explicitly represented in the model. Ideas are revised in light of what is learned from the model. The scientific model helps individuals conceptualise reality and serves as a bridge between the mind and the material world.

The literature in relation to students' understanding of the nature and function of consensus models is not extensive. However, studies that have undertaken research in this area have pointed to a limited understanding of the nature and function of consensus models (Grosslight, Unger, Jay & Smith, 1991; Ryan & Aikenhead, 1992; Smit & Finegold, 1995). A similar study to Grosslight et al., undertaken by Van Driel and Verloop (1999), explored teacher's knowledge of models and modelling in science. They found that "experienced science teachers, though they share the general notion that a model is a simplified representation of reality, may have quite different cognitions about models and modelling in science" (Van Driel & Verloop, 1999, p. 1150).

Grosslight et al. (1991) undertook a study to determine how secondary school students conceptualise the nature of consensus models. Clinical interviews were undertaken with 33 mixed ability 7th grade students (12-13 years), 22 students from an 11th grade (16-17 years) honours class and four adult 'experts'. The experts included a museum director, a high school physics teacher, a professor of engineering and education and a cognitive science researcher. Grosslight et al. identified three levels of thinking about consensus models which emerged from the interviews and reflected different epistemological views about the nature and function of consensus models. A Level 1 understanding of models had models as either toys or simple copies of reality. In a Level 2 understanding an individual distinguishes between the ideas or purposes motivating the model and the model itself, and realises that the purpose of the model dictates some aspect of the form of the model. A Level 3 understanding views models as constructed in the service of developing and testing ideas and explanations about phenomena. The researchers found each of the adults operating at a Level 3 understanding but there were no students operating at this level or even a mixed Level 2/3. The majority of the 7th graders were at Level 1 whereas the 11th graders were equally divided between Level 1, mixed Level 1/2 and Level 2 understanding. The interviews also revealed that the students appeared to have very limited experiences with consensus models as evidenced by the limited number of consensus models provided by both the 7th and 11th graders. The main function of consensus models, as perceived by the students, was to transmit information about the world as it really is and make such information more understandable. Grosslight et al. concluded that the students' conceptions of consensus models were consistent with a 'naive realist' epistemology (Nadeau & Desautels, 1984), with the experts' views being more consistent with a constructivist framework.

Ryan and Aikenhead (1992) explored more than 2,000 grade 11 and 12 students' views of a variety of issues that included the nature of scientific models. The probe instrument was in the form of a questionnaire where students were asked to make written comments to statements about science, technology and society. These statements, known as 'views on science-technology-society' were developed empirically over a six-year period with grade 11 and 12 Canadian students. In relation to the nature of scientific knowledge these researchers found that 19% of the students believed that models are copies of reality, thus holding a naive realist view (Nadeau & Desautels, 1984). They also found that 36% of the students did not believe that models are copies of reality while 37% held some vestige of naive realist thinking with a view that models come close to being copies of reality. In contrast to the findings of Grosslight et al., and Ryan and Aikenhead, Van Driel and Verloop (1999) found the teachers in their study who had a more pronounced knowledge of scientific models appeared to have integrated elements of both positivist and constructivist epistemological orientations.

In another study of student understanding of consensus models Smit and Finegold (1995) administered a questionnaire dealing with physics consensus models in general and with specific consensus models in optics to 196 South African post-graduate Higher Education Diploma students studying to become physical science teachers. The results of the study revealed that the students had very little knowledge of the origin, nature and function of consensus models in physics. This was reflected in the students' understanding that: (a) the most important function of consensus models in physics is not in the construction of scientific knowledge but in a teaching strategy for learning, (b) there is no clear distinction made between scientific models and the models produced by engineers in technological development, (c) a consensus model is depicted as very nearly similar to the real entity, and (d) there is confusion about the relationship between theory and a model.

The studies undertaken by Grosslight et al. (1991) and Gilbert (1991) also explored students' understanding of the different representational modes of a model. They mostly found students who had a narrow view of models as having a representational model as three-dimensional concrete objects constructed for recreation or instruction. These researchers rarely found students referring to models as representations of ideas or abstract entities that are reflected in mathematical or theoretical models.

The Study

This study (Hubber, 2002) investigated six Year 10 students' understandings of optics before and following three separate teaching stages that occurred over a three-year period. The students attended a mid-sized rural secondary school in north central Victoria, Australia, where they were initially part of a Middle School science elective class where optics was taught and, in subsequent years, participated in Year 11 and 12 physics classes, which also included the teaching of optics. Constructivist teaching and learning approaches were used in each teaching stage that involved concepts in geometrical optics (Middle School and Year 11) and scientific models in physical optics with quantum ideas (Year 12). The researcher acted in the dual roles of teacher and researcher. The exploration of students' understandings of optics was with respect to seven key concepts of geometrical optics during the Middle School and Year 11 classes. The students' impressions of the teaching and learning environment were also explored. The students' understanding of geometrical optics following the Year 11 teaching stage then formed the basis of exploration of their mental models of the nature of light in addition to their understandings of the nature and function of scientific models.

While the study occurred over three years, each having a teaching period, this paper will only report on the third and final year. That is, the year in which physical optics with quantum ideas were taught at Year 12 level. The research design for the third year centred on three semi-structured interviews and three questionnaires. The teacher/researcher also made classroom observations. The first two of the interviews occurred before the teaching period and the third interview was held after the teaching period. The questionnaires were administered before and during the teaching period.

The first of the interviews explored the mental models of the nature of light constructed by the students in explaining situations as they related to the key concepts addressed in the first two years of the study. The questions asked of the student in the interview included:

> 1. What do you think a model is when we use it in science?
> 2. Were there any models that we used in sound? Can you explain what they were? What models do you think of when considering electric currents in circuits?
> 3. I want to now ask you questions about how you imagine light to be. That is, what models you think about when explaining what light does in certain situations. How do you picture in your minds the way in which light travels:
> (a) away from a light bulb in a room (as shown in the diagram) straight after the light has been turned on?
> (b) from a torch into water (as shown in the diagram)?
> (c) from the candle to the screen in the converging lens system (as shown in the diagram)?
> 4. Where do you think you got this idea (model) from? Has it been in class, outside, or a combination of both?

The second interview was conducted just prior to the Year 12 teaching stage and once again explored the mental models students had about light, particularly after their experiences with a sound wave scientific model that was explored and used in the early part of Year 12. Follow up questions to those asked in the first interview were given to investigate any changes to the models expressed by the students at that time. The second interview also explored the students' understanding of the nature and function of scientific models. A set of statements about models, taken from a study undertaken by Smit and Finegold (1995), were given to the students where, for each statement, they were required to state whether they agreed, disagreed or were not sure. An example of some of the statements were (Smit & Finegold, 1995):

> 1. All models are creations of the human intellect.
> 2. All models are representations. Some, like drawings on paper, are purely visual, others made of material like plastic, wood, polystyrene, metal etc. can be seen and felt.
> 3. Any representation that one makes of an object or a structure or a process is called a model. (p. 624)

Other questions that probed the students' understanding of models were given where the students were to provide an extended response. For example, 'If you were making a model of some phenomenon, or process, or structure what would you need to think about?'

The final interview was conducted after the Year 12 teaching stage. The mental models constructed by the students were explored for different phenomena of light and evaluated against the current scientific models. Other questions were asked in relation to the students' understanding of the scientific models of light as well as their understanding of the nature and function of scientific models.

The questionnaires were administered to each of the six case study students in addition to other class members prior to the Year 12 teaching period. The first questionnaire followed the first interview in which the mental models of the nature of light of the six case study students were explored. It contained questions that centred on students selecting an appropriate model, with reasons, for different phenomena of light. The phenomena were listed as:

(a) Light spreads out in all directions from a light source;
(b) From each point on a luminous source light travels in al directions;
(c) Light bens in going from air into glass. Light slows down in glass; and
(d) White light is composed of different colours.

The students were also asked, 'where do you think your model of light originated from?'.

The second questionnaire, administered to all students in the class, had questions relating to the nature and function of scientific models. Examples of the questions asked were:

1. What comes to mind when you hear the word 'model'?
2. From the following list of items circle whether you believe the item is a model or not and provide a reason if you can [16 items were listed].
   (i) an engineer's construction of a bridge out of match sticks, Yes No Unsure
   (ii) Elle McPherson, Yes No Unsure.
   (iii) a scientific formula, like F = ma, Yes No Unsure
   (iv) sound waves, Yes No Unsure
3. What would you describe what a model is to someone who didn't know what a model was?
4. Given that models are used in science
   (i) What are they for?
   (ii) Why would a scientist have a need to develop a model?
   (iii) Do you think scientists would ever have more than one model for the same thing?
   (iv) Would a scientist ever change a model? Why?

The third questionnaire was administered during the teaching period and included questions relating to the students' mental models of the nature of light and the nature and function of scientific models.

The first part of the Year 12 teaching stage revolved around discussions relating to the students' understandings about the nature and function of models in science as well as the nature of light on the basis of their responses to the questionnaires. Theses discussions led to a view of the nature and function of models in science that matched that of scientists (Grosslight et al. (1991) referred to this view as a Level 3 understanding of modelling). The discussions also allowed students to be aware of their own mental models of the nature of light as they related to the key concepts explored in the previous years.

For the rest of the Year 12 teaching stage the different scientific models, including the student-generated mental models, were evaluated in terms of their scope, and predictive and explanatory power in explaining various phenomena of light already met in Middle School and Year 11 as well as new phenomena. The new phenomena included diffraction and interference effects of light, and the photoelectric effect. Difficulties encountered with any of the scientific or student's mental models in the explanation of specific phenomena of light were discussed and possible changes to models were explored. The opportunity was given for students to alter and revise their existing mental models as well as invent new ones.

In keeping with the historical context of 'landmark developments', as required by the state-wide prescribed course outline, the development of the scientific models from the time of Newton and Huygens to present day thinking were discussed with reference to the explanations given to observations made in key experiments. All the key concepts of the study were addressed in this teaching stage in terms of the scientific models used to explain them.

Results

A full discussion of the mental models constructed, and reconstructed, over the time of the study is not given in this paper; a full discussion can be found in Hubber (2003). However, a summary of the students' mental models of the nature of light is included in Table 1below as this will inform aspects of the students' understandings of the nature and function of scientific models. A full discussion of which is given below.

Students' Mental models of the Nature of Light over a Three-year Period

Table 1
Students' Mental models of the Nature of Light before and following the Year 12 Teaching Stage

Student	Mental models of the Nature of Light		
	During Year 10 & 11	During Year 12	
		Before Year 12 Teaching Stage	Following Year 12 Teaching Stage
Alan	Light is composed of rays.	Light is composed of rays that are continuous streams of material.	Light is composed of photons that are particle-like in nature but act as a wave or ray in great numbers.
Beth	Light is composed of rays.	Light is composed of rays that are streams of particles.	Light acts like waves or particles. Photons are theoretical entities that have particle and wave characteristics. Rays are little packets of energy that travel in waves.
Christine	Light is composed of rays.	Light acts like waves or particles.	Light acts like waves or particles. particles. The particles are theoretical entities called photons with electrical characteristics that act like a wave in great numbers. Rays are waves or particles moving in a straight line.
Danielle	Light is composed of rays.	Light acts like waves or particles.	Light acts like waves or particles. Photons are theoretical entities that have particle characteristics. Rays are streams of energy particles.
Evan	Light is composed of rays.	Light is composed of rays, called ray beams, that are continuous streams of material.	Light acts like waves or particles. The particles, called photons, have particle and wave characteristics. Rays consist of photons.
Frank	Light is composed of rays.	Light travels like waves in a direction shown in diagrams by arrows called rays.	Light acts like waves or particles. Photons have wave, particle and electrical characteristics. Rays give the direction of light propagation.

The students' understanding of the nature and function of scientific models may bear some relationship to the nature of their mental models of light and so an exploration of this understanding was undertaken for each participating student. The next section provides the results of this exploration.

Students' Understanding of the Nature and Function of Scientific Models before the Year 12 Teaching Stage

The scientific models of light provided the context to explore ideas about the nature and function of scientific models. In determining the students' understanding, they were questioned about their ideas in the following areas: (a) different kinds of models, such as scale and theoretical models, (b) relationships between the model, reality and the idea or concept being represented, (c) why scientists construct models, (d) functions of scientific models, (e) function of multiple models, and (f) temporary nature of scientific models. The students' understanding of scientific models was also informed by their mental models of the nature of light, as outlined previously.

In determining the students' general understanding of the term 'model' a questionnaire was administered that required them to make decisions about each of 15 items as to whether they constitute a model. Table 2 provides the results of this questionnaire. All the items in the questionnaire represented some type of model and were generated by the researcher based on categories of models described by Black (1962) and Harrison and Treagust (1996). They were: (a) scale model, (b) standard, or ideal, model, (c) mathematical model, (d) analogical model, (e) diagrammatic model, and (f) theoretical model. In the table the following codes are used: Y = yes, the item is a model, N = no, the item is not a model, and U = unsure, the status of the item as a model is unknown.

Table 2
Survey Results of the Model Status of various Items

Model	Model Type	Student					
		Alan	Beth	Christine	Danielle	Evan	Frank
An engineer's construction of a bridge made out of matchsticks.	Scale	Y	Y	Y	Y	Y	Y
A Mercedes Benz toy car.	Scale	Y	N	Y	Y	Y	Y
A person you admire and would like to be like in some way.	Standard	Y	Y	Y	Y	N	Y
Elle McPherson.	Standard	Y	Y	Y	Y	Y	Y
A scientific formula, like F=ma.	Mathematical	Y	N	N	N	N	U
Graph with a line of best fit showing how the rebound height of a basketball changes with the pressure inside the basketball.	Mathematical	N	U	N	U	N	N
Computer software used by weather forecasters.	Mathematical	Y	N	N	U	N	N
A chemical formula, like NaCl.	Mathematical	U	U	N	N	N	Y
A chart found in the biology classroom showing parts of the eye.	Diagrammatic	U	N	U	N	Y	N
Blueprint plans for a house.	Diagrammatic	Y	N	N	N	N	N
Plastic spheres connected by rods that are found in a chemistry laboratory.	Analogical	Y	Y	Y	Y	Y	Y
Water flowing in pipes as a representation of electric current in wires.	Analogical	Y	Y	Y	Y	Y	Y
Magnetic fields lines around a magnet.	Theoretical	N	U	Y	U	N	N
Sound waves.	Theoretical	N	U	Y	U	N	U
Light rays.	Theoretical	N	U	Y	U	N	U

The results shown in Table 2 indicate that each student had an acceptance for items that were three-dimensional and physical in nature, such as scale, standard and analogical models. However, the students varied widely in their acceptance of other items as models.

Alan's Understanding of Scientific Models before the Year12 Teaching Stage

Alan's understanding of scientific models is one where a model is a representation of something in nature and so he does not make any distinction between the model, reality and ideas or concepts about reality. When asked to explain the term 'model' he wrote, "A model is something that describes how something acts or reacts and looks like" and models are used in science "just to get a physical view of what goes on". There is a belief that scientists construct models "to prove what was being said was correct" and a scientist may have more than one model because "it depends on which way they look at a situation". The need to change a model, according to Alan, is "because it might be wrong". He believed that the main purpose of scientific models is in learning and teaching but there is a recognition that models play some part in predicting "...how things will happen".

Alan's general view of a model extended to several different types (refer to Table 2). He referred to the predictive function of a model when justifying the choice of computer software used by weather forecasters and a physics formula as models. Alan wrote, "Yes, it [computer software] models how weather is going to change" and a formula, like F=ma, "models the way each variable changes". However, a line of best fit on a graph did not constitute a model as it was "too uncertain", "it's kind of guess work, it depends on how accurate you want to be". Further questioning revealed that Alan believed in the need for the requirement that the model accurately matches the thing being modelled in nearly every aspect "if you want to have an accurate kind of result from it [the model]". Alan was the only student who considered that blueprint plans for a house constituted a model (refer to Table 2). He wrote that blueprint plans are a "2D model explaining/describing what a house looks like". Alan's consideration of blueprint plans as constituting a model may stem from his experiences with graphic drawings. One of his subjects during Year 11 and 12 was 'Graphic Communication' where Alan was often called upon to represent three-dimensional objects in a two-dimensional way.

Alan did not specify any of the theoretical models as constituting a model because he believed that sound waves, light rays and magnetic field lines are "what actually happens". The view that light rays exist is consistent with Alan's pre-instructional mental model of light (refer to Table 1).

Beth's Understanding of Scientific Models before the Year 12 Teaching Stage

Beth understands that a scientific model gives a representation to an idea or concept about reality rather than reality itself. When asked the use of models in science she wrote, "To show the concept of something". The motivation for a scientist to develop a model is "to back up his theories and explain something better" and so a scientific model has a role in teaching and learning. However, when asked if teaching and learning were the only functions of scientific models, Beth indicated that scientific models have a further role in research when she said, "...you need it [the scientific model] to step up and explain and obtain other things. You have got to start with something small and then it [the scientific model] builds up to do more research and stuff on".

Beth believes that the genesis of a model is with an idea, which leads to testing of the model. The results of the model testing then leads to a cyclic process of refinement and/or change of the model and ideas about a particular phenomenon. When asked the origin of a model she said, "Well, it could start as an idea and then you could find out through facts and stuff and you would have to experiment to claim that it is true and stuff". The constant change to scientific models is inevitable "as you find out more things about it [the phenomenon] and different ideas...like the models say of the atom, they have changed like about eight times". While Beth understands the temporary nature of scientific models she is "not sure" whether a scientist would have more than one model for the same thing.

The views expressed by Beth about the nature and function of scientific models closely match those of scientists. However, these views contrast with her understanding of the nature of light and her understanding of models in general which is limited to just a few types. Beth's mental model of the nature of light consists of particles of light that actually exist. Such a view suggests there is a direct relationship between the model and reality. In a questionnaire to indicate the model status of various items (see Table 1) Beth only recognised scale, standard and analogical models. For example, she stated that an engineer's construction of a bridge made out of matchsticks was a model because it "shows how the bridge will be constructed". For plastic spheres connected by rods that are found in a chemistry laboratory Beth indicated that these represent a model as they "show the concept of something". Mathematical items, such as a scientific formula, or diagrammatic items, such as a chart showing parts of the eye, were not considered as examples of models. In making comment on the status of a physics formula Beth wrote that it did not represent a model as the formula "does not show anything". She was unsure of the model status of the theoretical items on the questionnaire such as sound waves and magnetic field lines.

Christine's Understanding of Scientific Models before the Year 12 Teaching Stage

Christine's understanding of scientific models is one where a model is a representation of something in nature and so she does not make any distinction between the model, reality and ideas or concepts about reality. When asked what models are used for in science Christine wrote, "A model is a simple picture of how something works, enabling us to understand how it works in real life". Christine does acknowledge the multi-functional nature of scientific models but believes that the main function is, "for students to understand how it [phenomenon] works in real life". She considers that a scientist may need to change his or her model "if a new discovery is found which makes the current formula untrue. So changes need to be made to the model". This response suggests that an individual can gain direct access to reality and, as models are representations of reality, then any new discoveries of reality mean changes are necessary for the model. When asked if a scientist would have more than one model for the same thing Christine said, "Yes, most likely" but in the context of finding the best model that matches reality rather than exploring different ideas about reality.

Christine's general view of a model extended to several different types (refer to Table 1) including analogical and theoretical models. However, she believes that models need to be something physical. For example, magnetic field lines, sound waves and light rays were only considered to be models if the lines, waves or rays "were drawn [on paper]". Water flowing in pipes to represent electric currents in wires was considered by Christine to be a model because "both [water and electric currents] work the same way". Mathematical items such as scientific formula, chemical formula or graphs with lines of best fit were not considered by Christine to be models. A graph with a line of best fit "...is not a model, it is a result" and a physics formula is not a model, "it represents something, but we can't actually see how it works". Blueprints for a house did not constitute a model for Christine because "they are instructions, not a replica". Her pre-instructional mental model where light acts like waves or continuous streams of material is consistent with her requirement that models need to be physical. While this requirement represents a narrow view of the nature of scientific models she does make a distinction between the thing being modelled and the model. For example, Christine does not believe that light actually consists of waves or continuous streams of material, but rather, light behaves like waves or continuous streams of material.

Danielle's Understanding of Scientific Models before the Year 12 Teaching Stage

Danielle believes that scientific models are concrete copies of reality. When asked what models are used for in science she wrote, "To show the structure of something larger or smaller...[For example] to show the structure of atoms on a larger scale or a model of the universe on a smaller scale". The main function of the scientific model for Danielle is to "understand it [phenomenon] better". She also believes that a scientist would have a need to change a model "if they find that it [the phenomenon] is actually different". This response suggests that one can gain direct access to reality and so when one discovers something new in reality then the model, as a direct copy of reality, must change. Danielle was unsure if a scientist would have more than one model for the one phenomenon being modelled.

The view that models are concrete representations of reality was apparent when Danielle was asked to determine the model status of various items given in a questionnaire (refer to Table 2). Scale and standard models were accepted as models but not diagrams, mathematical items or theoretical items. Her mental model where light acts like waves or continuous streams of material is consistent with her requirement that models need to be concrete. While this requirement gives a narrow view of scientific models it is significant that Danielle does not believe that light actually consists of waves or continuous streams of material as this view is more closely related to the scientific view of a model. However, this view is in contrast with her belief that a scientific model is a direct copy of reality.

Evan's Understanding of Scientific Models before the Year 12 Teaching Stage

Evan believes that scientific models represent ideas or concepts about reality as when asked what use are models in science he wrote, "To understand concepts in an easier way". The main functions of scientific models, according to Evan, are, "just basically teaching, learning and observations, so basically teaching". When further asked what scientists do with models he said a scientist would "...make a model for his own understanding and to prove to other people as well". Evan also believes that a scientist would have multiple models to use as teaching models for people to understand his or her ideas rather than in representing rival ideas. A scientist needs to develop a model "...to prove something, to show people something is useful [like] phenomena, just basically physics ideas". Models are used "to let people understand them [ideas]". Scientists have more than one type of model to "look confident because if he only had one he would only be assuming it". The other models "back it [his idea] up basically". The different models are "for different people to understand" and selection of a particular model by a scientist is based on the model "that people find easier to understand". According to Evan the scientist would just use the appropriate model for the audience to convey his or her ideas.

Evan holds a general view of a model that extends to a limited number of different types. When asked the model status of various items in a questionnaire (refer to Table 2) Evan recognised scale, standard and analogical models among the list of items. An engineer's construction of a bridge out of match sticks was a model "...because it is of the same ideas, just on a smaller scale". Mathematical entities such as formulae and graphs were not considered to be models as they "...do not show anything". Evan believed that the theoretical items such as magnetic field lines, sound waves and light waves were not examples of models because each of these items "are real". This view is consistent with Evan's pre-instructional mental model of light where light is made of rays consisting of continuous streams of material.

Frank's Understanding of Scientific Models before the Year 12 Teaching Stage

Frank believes that scientific models are representations of reality rather than ideas or concepts about reality as when asked the use of scientific models he wrote that they "help understand how things work. To produce something on a different scale". For example, Frank wrote that plastic spheres with rods found in a chemistry laboratory constituted a model as "it is showing the structure of an atom". A scientist would have a need to develop a model, "[to] make sure calculations were correct and to see what should happen". In terms of the correspondence between the model and reality Frank does not believe that the model provides a complete description of the thing being modelled "because that is part of being a model. It does not have to show everything". This view is consistent with his response that a scientist may have more than one model for the same thing as the model "may match up different circumstances". Frank acknowledged that scientific models are multi-functional in that scientific models play a part in understanding and teaching as well as predicting phenomena, structures or processes that have not been observed before.

Frank's understanding of models in general is limited to three-dimensional physical models such as scale, standard and analogical models (refer to Table 2). These models physically "show the structure... [or] the workings". Diagrammatic models such as a chart showing parts of the eye and mathematical models such as graphs with lines of best fit were not considered to be models as "they do not show how it happens life like". Frank's pre-instructional mental model of the nature of light where light travels like waves is consistent with his limited view of models as physical entities. However, his view that light travels like waves (refer to Table 1) is consistent with the scientific view.

Summary of Students' Understanding of Scientific Models before the Year 12 Teaching Stage

Before the Year 12 teaching stage there was significant variation in the students' understanding of the nature and function of scientific models with respect to different facets of scientific models. These facets were: (a) the relationship between the scientific model, reality and ideas or concepts about reality, (b) representational modes of models, (c) function of scientific models, (d) temporary nature of scientific models, and (e) multiplicity of scientific models. Christine, Danielle and Frank believed that a scientific model represented reality as opposed to concepts and ideas about reality. While Christine and Frank recognised that scientific models fulfil a specific purpose Danielle believed that scientific models are scaled copies of reality. Alan had a similar view to Danielle in the belief that a good model needs to accurately match reality. In contrast, Beth and Evan expressed views that scientific models in general represent concepts and ideas about reality. However, Beth and Evan, along with Alan, had mental models of light where light actually consists of particles, as in the case for Beth, and continuous streams of material, as in the case for Evan and Alan. Such views suggest there is a direct relationship between the model and reality.

In terms of their understanding of different representational modes of models each student had an appreciation of the models described as scale, standard and analogical type models. Beth, Danielle and Frank were limited to three-dimensional concrete models whereas Christine was the only student who considered theoretical type models. Alan and Evan were the only students to consider two-dimensional models in diagrammatic form. In respect of mathematical models, Alan believed that the predictive capacity of such entities as scientific formulae and weather forecasting software constituted their status as models.

Each student expressed a view that scientific models are multi-functional in respect of understanding phenomena, teaching and testing. Four of the students, Alan, Christine, Danielle and Frank, believed the main goal of the scientific model was in understanding what something looks like or what it does. Evan goes further in believing that scientific models are for understanding and teaching. From the teaching perspective, the specific audience frames the choice of a model from a selection. Beth recognises the teaching function of scientific models but she believes that scientific models have a greater degree of functional importance in understanding and research. For Beth, understanding and research allow for the construction of more knowledge about the phenomenon under study.

Each student understood the temporary nature of scientific models. Christine and Danielle had an understanding that the model directly matches reality and, therefore, any new discoveries imply changes to the model. Beth was the only student who had the view of a cyclic process of knowledge construction involving the revision of scientific models and rethinking of ideas.

None of the students had an understanding that a scientist would have different mental models that embody the same idea or correspond to different theories. Alan and Frank had an understanding that a scientist may have models to represent different aspects of the thing being modelled. Evan expressed a view that a scientist would have multiple models as a means of communication so that a particular model would be chosen with a specific audience in mind. Christine and Danielle believed that a scientist would have multiple models in order to test which version closely matched reality.

Students' Understanding of the Nature and Function of Scientific Models following the Year 12 Teaching Stage

The students' understanding of the nature and function of scientific models following the Year 12 teaching stage was based on two questionnaires given during the teaching stage, a questionnaire given at the end of the teaching stage and an interview administered four weeks later. As part of the final questionnaire, students were required to determine the validity of statements relating to models (taken from Smit & Finegold, 1995, p. 624-625). Each student determined the validity of each statement and indicated if the statement was correct (C), incorrect (I) or unsure (U) of its status (refer to Table 3). The results shown in Table 3 suggest that many of the responses are consistent with a scientific and constructivist perspective. To provide further details of each student's understanding of the nature and function of scientific models the following sections profile each student separately and in alphabetical order.

Table 3
Students' Responses of the validity of Statements made about Models

Statement	Alan	Beth	Christine	Danielle	Evan	Frank
1. All models are the creation of the human intellect.	C	C	C	C	C	C
2. All models are representations. Some, like drawings in paper, are purely visual, others made of material like plastic, wood, polystyrene, metal etc. can be seen and felt.	C	C	I	C	I	C
3. Any representation that one makes of an object or a structure or a process is called a model.	C	C	C	C	C	C
4. Models exist in nature.	C	C	C	U	C	I
5. All models are mental images (i.e. models only exist in the human mind).	C	C	I	U	I	C
6. Models are aids that are used to obtain knowledge of nature.	C	C	C	C	C	C
7. Models always provide a complete description of the object, structure or process in nature that it models.	C	I	U	I	I	I
8. This statement relates to the origin of models: a model is formulated using facts obtained through experiment and/or observation.	C	C	C	C	C	C
9. The term model and theory are the same thing.	U	I	I	U	I	I
10. The only function of models in science is in teaching about phenomena and complex processes.	I	I	I	I	I	I
11. Models are temporary by nature. Scientists use a models for a time, but as a consequence of the increase in scientific knowledge the model becomes obsolete or useless and is either adapted or replaced by another model.	U	C	C	C	C	C
12. A scientist always has more knowledge of an object, process or structure than is represented by the model itself.	C	C	I	C	I	U
13. An important function of any model is to describe something (an object or a structure or a process) in nature.	C	C	C	C	C	C
14. Models play an important role in the explanation of phenomena.	C	C	C	C	C	C
15. Models can be used to predict phenomena, structures or processes that have not been observed before.	C	C	C	C	U	C

Note: The codes in the table mean: the students believe the statement is either (C) correct, (I) incorrect, or (U) unsure. From a scientific and constructivist perspective all the statements are correct except for statements 4, 7, 9 and 10.

Alan's understanding of Scientific Models following the Year 12 Teaching Stage

Alan has maintained his view that scientific models represent reality. He believes that a scientist needs a model as "...an explanatory thing...to see what actually happens". He still believes that good scientific models "have to be fairly close to being exact" with the thing being modelled. This view is consistent with Alan's hybrid mental model of the nature of light as well as his acknowledgment that the statement 'Models always provide a complete description of the object, structure or process in nature that it models' is correct (refer to Table 3).

Alan did expand his general view of a model to include more representational types. He now considered chemical formulae are models because "they just represent different types of atoms" and he also acknowledged that magnetic field lines, sound waves and light rays are models. However, Alan still maintained that a graphical line of best fit was not an example of a model as it would not make accurate predictions and models need to "make fairly close to exact [predictions]".

Alan's views about scientific models suggest that the main purpose of scientific models is to accurately as possible replicate reality so that one can understand what is actually happening. For Alan, the modelling process does not drive research but is a response to the construction of new knowledge so that when new discoveries are found the model must change to accommodate the new construction.

Beth's understanding of Scientific Models following the Year 12 Teaching Stage

By the end of the Year 12 teaching stage, Beth had reaffirmed her previous views about the function of scientific models. When asked why scientists need models she stated that scientists "need them to help them go into something better but they also need them to explain their theories to other people that it is credible and things" and when further asked which function is more important Beth stated it was to extend understanding "so they [scientists] can find out about more things". Beth recognised that models are generated from ideas "and then [scientists] go to investigate it and things to see if they're right" and scientists "...have probably got a couple of models of what it [the thing being modelled] could be and see which one fits better". Further evidence of Beth's understanding of the main function of scientific models came when she was asked to comment on the statement 'The most important function of models in physics is in research and the construction, and reconstruction, of knowledge rather than in teaching students'. She wrote, "I agree with this statement as models allow people to explain phenomena and research them to find out more".

By the end of the Year 12 teaching stage, Beth had a general understanding of a model that included a greater range of representational types than she had before the teaching stage. She now considered that two-dimensional models such as house plans were models because "...they give you a picture of what you are going to make". She also considered that chemical formulae, light rays, sound waves and magnetic field lines were models. In terms of a light ray Beth had changed its status to be a model as it is "...just a representation. [A] picture that helps to visualise how it works". One type of model that Beth still did not consider a model was physics formulae because she was "...not sure what they tell you when you think of a formula. I just think of a formula, I don't think of it in any other way". This response suggests that, for Beth, a model needs to be visual in some way, and therefore physically two-dimensional or three-dimensional. In general, many of the views held by Beth in relation to the nature and function of scientific models closely matched scientific and constructivist thinking.

Christine's understanding of Scientific Models following the Year 12 Teaching Stage

Christine still maintains the view that scientific models represent something in nature as she said that scientists would need to develop a model of a phenomenon "...so they can explain how it works". She believes that the statement 'A scientist always has more knowledge of an object, process or structure than is represented by the model itself' is "incorrect". This response is consistent with Christine's construction of a hybrid mental model of light that encapsulates both wave and particle ideas. Christine recognises the temporary nature of models (refer to Table 3) which maybe why she was unsure if models always provide a complete description (refer to Table 3) as new knowledge creates a need to change the model. Christine maintains the view that the main function of scientific models is with understanding and teaching but she does recognise that models can be used to predict phenomena, structures or processes that have not been observed before (refer to Table 3) and so have some role in research.

Christine's general understanding of models has changed very little in respect of the types of entities she considers to be models. She believes that models need to be concrete and now includes diagrammatic entities such as charts as models. However, Christine still considers entities such as formulae and graphs with lines of best fit are not models.

Danielle's understanding of Scientific Models following the Year 12 Teaching Stage

Danielle has maintained her view that scientific models are physical representations of entities in nature. This was evident when asked if her understanding of complex phenomena of light such as diffraction, photoelectric effect and polarisation would be greater by using and working with scientific models. Danielle wrote, "Yes, because we'll be able to see what really happens". She distinguishes between the scientific model and reality as when asked what makes the wave representation of light a model, she wrote, "It is not light, but it shows what happens". Danielle recognises that models are limited in that they do not provide a complete description and scientists always have more knowledge of the entity in nature than is represented in the model itself (refer to Table 3). This limiting characteristic of models is reflected in Danielle's mental models of light that consist of a particle model and a separate wave model.

Danielle's general understanding of models now includes a greater range of representational types. She initially thought that models could only be three-dimensional as when asked if models can only be three-dimensional shapes Danielle said, "I thought that, but probably not now". Danielle now considers that mathematical entities such as formulae and graphs with lines of best fit constitute models, as do diagrams and theoretical entities such as light rays and sound waves. Danielle recognises that scientific models are temporary in nature and are multi-functional in terms of understanding, teaching and contributing to research (refer to Table 3).

Evan's understanding of Scientific Models following the Year 12 Teaching Stage

Evan has maintained his view that scientific models represent ideas about reality. However, he also believes that the development and use of models allows scientists to find absolute truths about a particular phenomenon. This was evident in a response Evan gave to a question about why a scientist would develop a scientific model and he used the context of light. Evan said that scientists would develop a model "so they can study the phenomenon, they can get new ideas and then find out by then how light actually works. They can study with it". Further evidence of Evan's understanding that science is able to find absolute truths occurred after the teaching of the scientific models of light from an historical perspective. Evan remarked during class, "Do we know what light actually is today?" thus questioning if science had yet found the truth about light.

Evan's general understanding of models now includes mathematical models and theoretical models. He considers that mathematical entities such as formulae and graphs with lines of best fit represent models as "...you can predict or you can understand what things do". The ability for a model to predict was a test of the viability of the model because if the model did not predict correctly then, according to Evan, one needs to "scrap the model and go and get another one". Theoretical models such as sound waves, magnetic fields and gravitational fields "are models...graphic models".

In terms of light, the relationship between the model and reality has changed for Evan. He no longer believes that rays actually constitute light but that light can be understood in terms of wave and particle ideas. When asked why he switched from one scientific model of light to another Evan said, "Because I know that I don't know what light is and then like the models explain different phenomena of light". However, Evan has encapsulated both wave and particle ideas into a hybrid model of light which may relate to his view that it is possible for science to determine what light actually is. Evan continues to believe that understanding and teaching are important functions of scientific models although he now considers the function of research to be more important. When asked to comment on the statement 'The most important function of models is in the construction and reconstruction of knowledge rather than in teaching students' Evan wrote, "Yes, without research construction and reconstruction the scientists could not teach the students".

Frank's understanding of Scientific Models following the Year 12 Teaching Stage

Frank has shown elements of a scientific and constructivist understanding of the nature and function of scientific models. This was evident in responses he made about the validity of statements about models given in a questionnaire (refer to Table 3). When asked what was required to construct a model Frank said "...you need a few concepts" thus linking the model with concepts about reality rather than reality itself. He believes that the use of models is important in the understanding of phenomena as when asked the use of models he said, "To have models allows you to have knowledge of the subject". Frank recognised that the major function of scientific models is in research as when asked to comment on the statement, 'The most important function of models in physics is in research and the construction, and reconstruction, of knowledge rather than in teaching students, he wrote, "This is good because it allows you to understand the theory behind the models". The function of a model to make predictions that may result in changes to the model was understood by Frank when he said that scientists "...can change the model, they don't have to be stuck on the one thing...[scientists can say] will that happen as we predicted [or] will we go back here and change the model?".

Frank's general understanding of models now includes a greater range of representational types. From the questionnaire where he was asked the model status of various items (refer to Table 2) he commented in a later interview that "after thinking about it a bit more a lot of things were models where I said no to them". He now considers that mathematical entities like graphs with lines of best fit and weather forecasting software as models because they can make approximate predictions. However, Frank is still unsure about the model status of scientific formulae "...because you are not predicting anything you are getting the right answer from it". In terms of a chemical formula like NaCl Frank considers this to be a model "because you are showing its structure". Theoretical entities like magnetic field lines and light rays were now considered to be models but only if something physical is drawn. For example, for magnetic field lines, "...if you get the magnet drawing and draw the field lines around it to represent it...that's a model".

While many aspects of Frank's understanding of the nature and function of scientific models suggests a scientific and constructivist viewpoint, his complex hybrid mental model of a photon may suggest otherwise. His view of a photon with its particle, electric and wave characteristics suggest an attempt to conceptualise reality directly. On the other hand, it may be that Frank views his image of a photon in the same way that Beth does. That is, a wave-particle theoretical object that metamorphoses as either a wave or particle.

Summary of Students' Understanding of Scientific Models

The students' understanding of the nature and function of scientific models varied widely before the Year 12 teaching stage. In understanding the nature of scientific models a defining characteristic is the relationship between the model, ideas or concepts about reality, and reality. A constructivist perspective purports that models are representations of ideas or concepts one has about reality. The model is in the service of ideas or concepts about reality and these are explicitly represented in the model (Grosslight, et al. 1991, Carey & Smith, 1993). This perspective was described by Grosslight, et al. as Level 3 thinking about models as opposed to Level 1 thinking these researchers described as a view that models are replicas of reality and ideas are of what to show or not to show of reality.

While the students' understanding that rays are actual constituents of light, maintained throughout Phases 1 and 2 of the study, represents Level 1 thinking this was not reflected in the students' views about the nature of scientific models just prior to the Year 12 teaching stage. There was a range in thinking extending from Level 1 to close to Level 3 thinking. A view that reflected Level 1 thinking about models was expressed by Danielle when she commented that scientific models "....show the structure of something larger or smaller...to show the structure of atoms on a larger scale or a model of the universe on a smaller scale". Ryan and Aikenhead (1992) found evidence of secondary school student thinking that models are copies of reality, thus exhibiting what these researchers described as a 'naive realist' view. In contrast to Danielle's understanding of models Beth and Evan expressed views that reflected a Level 3 thinking or constructivist view. For example, Beth stated that scientific models are used "to show the concept of something". Van Driel and Verloop (1999) found this understanding among science teachers in their study as did Grosslight et al. (1991) with so called experts. However, Grosslight et al. did not find Level 3 thinking about models among any of the Year 7 or Year 11 students in their study. The other students in the study, Alan, Christine and Frank believed that models are representations of reality. However, these students did not have a view that models are replicas but representations mediated by some purpose. For example, Frank suggested models "...do not have to show everything" there can be different models for the one phenomenon that "...match up different circumstances". Grosslight et al. (1991) described this view of the nature of models as Level 2 thinking which was evident in the Year 7 and 11 students within their study.

In terms of understanding the functions of models each student recognised the role played by models in understanding phenomena. However, the students differed in their views as to the other major roles. Beth was the only student to understand the cyclic role played by models in the construction of scientific knowledge involving the testing of ideas that may lead to revision of scientific models and/or revision of ideas. This constructivist view was determined by Grosslight et al. as a Level 3 understanding of models. In contrast, the other students believed the major role of models was in teaching and learning. Several researchers (Aikenhead, 1987; Grosslight et al., 1991; Mackay, 1971; Smit & Finegold, 1995) also found a lack of understanding of the full range of roles played by models. The tentative nature of scientific models, expressed in Beth's cyclic role played by scientific models, was also expressed by each of the other students. However, for them the tentative nature reflected a view that the model matched reality therefore any new discoveries about reality would necessitate a change to the models that represent it. For example, Danielle believed that scientists change their models "if they find that it [the phenomenon] is actually different". This view that a model matches reality and may become 'outdated' when new data are obtained was also found by Van Driel and Verloop (1999) who explored science teachers' understanding of models. These researchers described this thinking as a 'logical positivist' view.

All the students, except for Beth, believed that a scientist could have more than the one model for the same target. However, this view was not such that multiple models may exist that embody the same idea or different theories. While Alan and Frank believed that a scientist may have multiple models to reflect different aspects of the target Christine and Danielle believed a scientist would have multiple models in order to test which version closely matched reality. Conversely, Evan believed that a scientist would have multiple models as different teaching aids, which would be selected on the basis of the audience to be taught.

Before the Year 12 teaching stage the students had a limited range of representational modes of a model. Each student believed in three-dimensional physical models in the form of scale, standard and analogical models. Only two of the students, Alan and Evan, could relate to two-dimensional diagrammatic models and there was little understanding of models as representations of abstract entities such as mathematical or theoretical models. The finding of a narrow view of models as three dimensional concrete objects was similar to that found by Grosslight, Unger, Jay and Smith (1991) with Year 7 and Year 11 students and Gilbert (1991) with college students.

The choice of three-dimensional physical models by the students fits well with common experiences both inside and outside the classroom. For example, the experience of playing with model toys such as cars and dolls in childhood. Students well recognise the media exposure of fashion models. The physical models commonly used in the science classrooms include analogical models of water in pipe systems for electrical current and ball and stick atomic models. In contrast, everyday language suggests that light waves exist which may have contributed to the students' lack of understanding that light waves, described in this thesis as theoretical models, are indeed models.

Given that the Year 12 teaching stage occurred during the last few weeks of the students' secondary schooling, their recall of models used in science classes was poor. Each student had prior experiences working with models in other topics in physics as well as in chemistry and biology in lower level science classes. Three of the students had undertaken chemistry in both Year 11 and 12 and one student undertook Biology and Chemistry at these year levels. The students' lack of recall of using models may stem from past experiences in science classes where, despite the use of models to understand the phenomena under study, there was no emphasis that models were being used. It maybe that models are presented as static facts (Van Driel & Verloop, 1999). For example, atoms are described as if the model portrays what they actually are rather than what we imagine them to be. Consequently, depending on the phenomenon, teachers describe atoms in different ways - as spherical particles in constant vibratory motion to explain such phenomena as Brownian motion, temperature or sound, for instance. In contrast atoms are described as entities consisting of mostly space with a central nucleus and orbiting electrons to describe electrostatic effects.

The inability of the students to recognise mathematical models appears at odds with their experiences in mathematical modelling within mathematics classes. In mathematical modelling, the students explore mathematical patterns using real life data through constructing graphs with 'lines of best fit' and constructing equations with the purpose of interpolating and extrapolating the data.

The mathematics teacher regularly sets problems that require a modelling process of solution as it represents a significant component of assessment. However, in solving these problems it may not be apparent to the students that it is a modelling process that they are undertaking and a graph with a line of best fit and/or equation represents a mathematical model.

Following the Year 12 teaching stage the students elicited many facets of a scientific understanding of the nature and function of scientific models. In applying the levels of viewpoints about the nature and function of scientific model used by Grosslight, Unger, Jay and Smith (1991) the students ranged in thinking from one close to Level 1 thinking, or naive realist epistemology, to one close to a Level 3 thinking, or constructivist epistemology. Alan's view that scientific models replicate reality as accurately as possible represents a Level 1 thinking of models. This view was also reflected in Alan's mental model of the nature of light consisting of a hybrid model of photons as real constituents of light that were particle-like in nature but behaved like waves in great numbers. Conversely, Beth and Frank showed evidence of Level 3 thinking of the nature and function of scientific models. These students had a view that scientific models represent ideas or concepts about reality and a main function of scientific models is in research to allow for the construction and reconstruction of scientific knowledge. Beth's Level 3 thinking was also reflected in her understanding of the nature of light evident in her scientifically appropriate application of the wave or particle scientific models depending on the phenomenon to be explained.

The students increased their general view of a model to include a greater range of representational modes. Significant in the change of thinking was the acceptance by all the students of two-dimensional modes of representation as models and the majority of the students' acceptance of theoretical models and some types of mathematical models. However, three of the students (Beth, Christine and Frank) still believed that scientific formulae did not constitute a model and two students (Alan and Christine) did not consider mathematical 'lines of best fit' as models.

An understanding of a greater range of representational modes as models may have been due to classroom discussions about the characteristics of models in general. This allowed the students to discuss their ideas about models and extending them to include a variety of representational modes. However, the reluctance to accept scientific formulae as models may stem from previous experiences such as the manner in which formulae are presented and used in the classroom. Rarely are formulae introduced on the basis that they are scientific models. For example, there is little or no discussion in relation to the assumptions and approximations that underlie the symbols of formulae that represent concepts we have about reality. Apart from some initial discussion as to what the symbols represent in terms of ideas and concepts about particular phenomena students routinely use scientific formulae in mathematical manipulations to get correct numerical answers to quantitative questions. There may be a view among the students that scientific formulae are nature's laws that provide us with truths about reality. This view is reflected in a statement by Frank that scientific models do not constitute models as "...you are not predicting anything you are getting the right answer from it".

In terms of understanding the nature and function of scientific models there was a change in students' thinking towards a more constructivist perspective. Evan and Frank joined with Beth in viewing scientific models as representing ideas or concepts about reality whereas Alan, Christine and Danielle believed that scientific models had a direct relationship with reality. Danielle no longer viewed models as replicas of reality and in the terminology of Grosslight et al. (1991) progressed from Level 1 to Level 2 thinking about models. Each student recognised the role played by scientific models in the construction of new knowledge through research.

The change in thinking by the students may have been due to the teaching of the nature and function of scientific models within the context of optics. The teaching of the scientific models of light within an historical perspective allowed not only for a discussion of the merits of the scientific models but also the modelling process and its involvement in the construction of scientific knowledge. The demand for two opposing models to explain all the phenomena of light highlights the division between the model and reality in terms of representing ideas or concepts one has about reality rather than directly representing it. The inclusion of the students' own mental models in the discussions allowed comparisons to be made with historical models and ideas, and testing of their models in explaining each phenomenon of light.

An area that may have contributed to the students' change in thinking about models other than the Year 12 teaching stage was the interviews and questionnaires given prior to the Year 12 teaching stage. The line of questioning about the nature and function of models may have initiated thinking about such models that was sufficient to lead the students to better articulate their views in later interviews and questionnaires.

Results Summary

The students' understanding of the nature of light and nature and function of scientific models changed over the period of the study. There was evidence in the first two phases of an understanding that rays were actual constituents of light that reflected a naive realist epistemology. This contrasted with the scientific model of a ray as a geometrical construction that provided the direction of light propagation. While the ray scientific model, through the use of ray diagrams, was used prolifically throughout the Middle School and Year 11 teaching stages, by the beginning of Phase 3 only three students, Christine, Danielle and Frank had constructed a scientific understanding of a ray. The persistence of the mental model that rays are constituents of light may have been due to the cultural understanding of perceptions of beams of light, drawings of suns or everyday language supporting a view of rays as real.

Over the Year 12 teaching stage there was evidence that each student had achieved a scientific understanding of the nature of light in terms of the application of the particle scientific model or the wave scientific model to explain various light phenomena. The students were confident in using either particle or wave ideas depending on the phenomenon to be explained and were aware that their models about the nature of light had changed over the teaching period. In contrast to the successful explanations of light phenomena in terms of either as a wave or particle model there was the construction by five of the students of a hybrid mental model of a photon. The students believed that the photon had both particle and wave characteristics. While Alan believed that photons were real the other students considered them to be theoretical entities.

There appeared to be some links between the students' understanding of the nature of light and their understanding of the nature and function of scientific models. For example, the Level 1 thinking of models shown by Alan reflected his photon mental model whereby photons were considered as constituents of light. In addition Beth's Level 3 understanding of models reflected her scientific understanding of the nature of light in terms of the wave and particle scientific models. The hybrid photon mental models constructed by Christine and Evan matched their Level 2 thinking of models. Danielle's scientific understanding of the nature of light through the application of the wave and particle scientific models does not match her Level 2 thinking of models. However, she may have the view that the one 'super' model that matches reality is yet to be achieved and the scientific models of light represent an interim understanding. As with Danielle, Frank's hybrid mental model of a photon is inconsistent with his Level 3 thinking of models and the separate application of wave and particle models in explaining different phenomena of light. It may be that he views his image of a photon as does Beth. That is, a wave-particle theoretical object that metamorphoses as either a wave or particle.

The Year 12 teaching stage was not successful in changing all the students understanding to a scientific view of the nature of light and constructivist view of the nature and function of the scientific models. This may have been due to a lack of time spent during the Year 12 teaching stage in terms of allowing sufficient time for classroom discussion of the nature and function of scientific models and the nature of light. A greater than normal time allocation could not have been given to the teaching of the scientific models of light and the nature and function of scientific models in particular. There was only one lesson given directly to a discussion of the nature and function of scientific models. The teacher was obligated to give equal weighting in time allocation to all topics in the state-wide prescribed curriculum so as to maximise students' performance on their state-wide set final examination. The results on the examination, held two weeks following the Year 12 teaching stage, had a significant bearing on the students' entry to post-secondary education and employment.

While links can be made between the learning of scientific models of light and scientific models in general there was no curriculum requirement to teach the nature and function of scientific models (Board of Studies, 1994). Therefore there were no examination questions related to the nature and function of scientific models and consequently the students did not revise their understanding of scientific models as part of their examination preparation. Given the time constraints in teaching the topic of physical optics and quantum ideas, there was insufficient time for the students to consolidate their new ideas and reflect on how their ideas had changed. Such processes as consolidation and reflection are seen as necessary conditions for the change of conceptions or mental models (Driver & Oldham, 1986; Posner, Strike, Hewson & Gertzog, 1982).

Implications for Teaching and Learning of the Nature and Function of Scientific Models

There was some evidence in this study of a linkage between the students' mental models of the nature of light and understanding of the nature and function of scientific models. Beth's constructivist view of the nature and function of scientific models was consistent with her scientific view of the nature of light. This contrasted with Alan's realist view of the nature and function of scientific model, which was consistent with his photon model of light where photons were considered as constituents of light. The majority of the other students possessed a positivist view of scientific models, which supported their hybrid models of the nature of light. What is apparent with these findings is the need for more research to explore further any linkages between students' understanding of the nature and function of scientific models and their understanding of specific scientific models. While all the students in this study did not achieve a scientific understanding of the nature of light their increased understanding was supported by discussions about the nature and function of scientific models.

Discussions about the nature and function of scientific models should occur at times when scientific models are used within the classroom. What needs to be emphasised is that a model is being used as a tool for understanding as distinct from 'this is actually how it is'. In the context of optics this should be during the teaching and learning of geometrical optics. The study of optics then becomes one of exploring and testing more and more complex models. If students can appreciate a constructivist perspective of the nature and function of scientific models then quantum mechanics becomes yet another model, a complex abstract mathematical one - but a model none-the-less.

While optics is an appropriate context to explore the nature and function of scientific models it should also occur within other topics in physics and science in general. For example, the topic of the structure of matter has a number of models of the atom. Beth gave this example in expressing her views of the function of scientific models. An enhanced understanding of the nature and function of scientific models through the context of optics may lead to a better understanding of concepts related to other areas in physics such as electricity, models of the atom, heat, and sound. The prevalence of students' understanding of optics that matched historical thinking, such as thinking about photons acting together to form wave phenomena, supports a curriculum approach that includes an historical account of how ideas were developed and superseded. Such an approach gives the student an insight into the modelling process and the nature of change and knowledge construction in science.

A possible factor in the students' increased understanding of the nature and function of scientific models in this study was discussions about the similarities between scientific models and different representational modes of a model from different contexts. Therefore, a teaching and learning strategy to enhance students' understanding of the nature and function of scientific models would entail discussions about the positive links between scientific models and other representational modes in other contexts, particularly those more readily identifiable to the students. For example, a teaching strategy that compares and contrasts mathematical and scientific modelling would enhance the understanding of both processes. In addition, the linking of mathematical modelling and scientific modelling may go some way to resolving a more general problem espoused by Woolnough (2000) of students' inability to apply their mathematical knowledge to physics ideas and concepts.

A number of positive links exist between scientific and mathematical models. For example, a strong characteristic of a mathematical model is its ability to make predictions. Given that students are familiar with making predictions with mathematical models, such as drawing lines of best fit and extrapolating data, then a link can be made to the predictive function of scientific models. As multiple mathematical models are possible for the one set of data, each with its own set of predictions, then the same applies to scientific models. Just as a mathematical model is restricted in its applicability to match the data a scientific model is also restricted in its application to its target.

The reluctance of students in this study to accept scientific formulae as a representational mode of scientific models suggest a change is required in the manner in which scientific formulae are introduced into the classroom. Rarely are they introduced as scientific models and so an emphasis needs to be placed in discussing the assumptions and approximations that underlie the symbols of the formulae that represent ideas and concepts about reality. Students may then see that scientific formulae are not nature's laws that provide us with truths about reality. The acceptance of scientific formulae as a representational mode of a model may be enhanced with the adoption of teaching and learning strategies whereby students see the production of scientific formulae as the product of a modelling process. This may be achieved through providing historical accounts of the evolution of formulae with a particular emphasis on illustrating the assumptions and approximations that underlie the formulae construction. Students should also be encouraged to participate in their own investigations where they test ideas and analyse data with the purpose of determining patterns either graphically with the drawing of lines of 'best fit' or constructing mathematical equations.

The teaching strategy of comparing mathematical and scientific models need not be restricted to just these two representational modes. A discussion of the similarities and differences for a whole range of representational modes of models allows for an understanding of the 'distinctiveness' of scientific models (Van Driel & Verloop, 1999). However, while a strategy that discusses the links between scientific models and other representational modes aid learning it is equally important to point out the areas where scientific models do not link to other representational modes.

Scientific models are representations of different ideas and therefore a number of models can be valid within their employed purposes. From this perspective, the desire for the one supreme model that encapsulates all experiences that we have of a phenomenon does not arise. The students' own mental models can then be valid if restricted in the purposes to which they are applied. While the coexistence of an alternative conception with a scientific concept is considered an unacceptable outcome to classroom teaching (Osborne & Wittrock, 1985) the use of multiple models is not (Gilbert & Boulter, 1995b). Within the classroom, the reconstruction of mental models need only be a restriction in the purposes to which they apply. These mental models may then stand side by side with the more powerful scientific models that provide a wider degree of application.

Finally, an essential element to this study is the relationship between the students' epistemological beliefs and conceptual change to the concepts and scientific models of optics. It may be that the students' difficulties in attaining a scientific understanding of physical optics and quantum ideas lay with a lack of understanding of a constructivist view of the nature and function of scientific models. From this perspective, a scientific understanding of optics at Year 12 involves two major changes for the students. These are an epistemological change from a naive realist or positivist position to a constructivist perspective, and an ontological change from an entrenched and highly successful view of a ray as an entity of light to the scientific models of the ray and nature of light. Several researchers have highlighted the difficulty in changing students' epistemologies (Carey & Smith, 1993; Smith, Snir & Grosslight, 1992; Wiser, Kipman, & Halkiadakis, 1988) and ontological categories (Chi, 1992; Slotta, Chi & Joram, 1995). The findings of this study in terms of students' change in understandings of optics certainly support the need for further research into students' changing epistemologies and ontological categories. Such further research should lead to an enhanced understanding of student learning and a better understanding of appropriate curriculum content and teaching strategies to apply. This will ultimately lead to better outcomes for student learning.

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