CHILDREN'S UNDERSTANDING OF SCIENTIFIC CONCEPTS : A DEVELOPMENTAL STUDY

by

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ABSTRACT

Combining theory-oriented inquiry and research that aims to improve instruction is a major goal of neo-Piagetian theory. Within this tradition, Case's (1992) developmental model enables educational researchers to conduct a detailed analysis of the structural and conceptual changes that occur in children's representation of knowledge in different domains at various points in their development. In so doing, it is now possible for educators to first assess children's "entering competence" in a specific subject and then set developmentally realistic instructional goals.

Using Case's (1992) model as a theoretical framework, a developmental study was conducted investigating children's understanding of scientific phenomena, specifically buoyancy, at the ages of 6, 8, and 10 years. The main goal was to determine whether or not children's conceptual levels of understanding change systematically with age in a progressive manner consistent with neo-Piagetian stages of development hypothesized by Case. Participants attended one elementary school in a suburban school district near Vancouver, B.C. Sixty children were individually administered a set of five buoyancy tasks that varied in level of difficulty and involved objects of different weights, shapes and sizes. Each student was asked to predict whether an object would float or sink in different liquids and to support their prediction with an explanation.

Analyses using the neo-Piagetian approach of articulating the semantic and syntactic nature of children's mental structures were conducted on the students' responses. Shape, size, weight and substance were identified as the semantic components of buoyancy which are syntactically related. Using Case's dimensional metric for classifying different levels of conceptual understanding of buoyancy, the results of the study confirmed that children's

understanding of buoyancy did progress through the developmental sequence as hypothesized. The structural progression from predimensional through to integrated bidimensional reasoning captured the general developmental pattern of children's understanding of buoyancy from the ages of 6 to 10 years. A statistical analysis of the responses showed significant differences between each age group. In summary, the results of the study suggested an age-related and hierarchical progression in conceptual understanding that was consistent with the age-level postulates of Case's (1992) developmental model.

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CHAPTER 1: INTRODUCTION

In the last decade, there has been a growing recognition that understanding plays an important role in learning and thinking, particularly with respect to the acquisition of scientific concepts. Educators are coming to the realization that there is more to learning science than simply mastering an organized body of content and a set of procedural skills. The view that knowledge cannot be directly transmitted to the learner but must be actively constructed by the learner underpins contemporary perspectives on science education. Pedagogical issues and instructional approaches in science education are now being addressed within a constructivist framework.

Information from Piagetian and neo-Piagetian studies indicates that young children acquire substantial knowledge of the physical world long before they could have gained it by "enculturation" (Carey & Gelman, 1991). From a nativist viewpoint, there is reason to believe that children come into the world preprogrammed to conceptualize physical reality in certain ways (Spelke, 1988). Young children have a range of knowledge schemes that can be drawn on to interpret everyday natural phenomena. Such "common sense" knowledge is based on personal experience and social interaction. Some researchers argue that there are commonalities in children's informal ways of reasoning partly because of shared ideas and sense-making conversations with peers (Arlin, 1990; Carey, 1985; Case, 1992; Pea, 1993).

Karmiloff-Smith (1991) proposed that nativism and constructivism are not necessarily incompatible. For example, in the case of density, children may come equipped with the ability to apprehend weight, volume and density, but may still need to sort out, through experience, which properties are most relevant in particular problem situations. In other words, everyday reasoning is characterized by pragmatism; that is to say that ideas are often constrained by the specificity of each situation and by the purpose of the task.

With the emergence of constructivism as a conceptual framework for explaining the process of science learning (Driver, 1982; Driver & Oldham, 1986; McClosky, 1983), four different research inquiries appeared in the literature: (1) a theory-based approach to cognitive development, (2) learning theory tradition investigating the novice-expert shift, (3) social constructivism and (4) neo-Piagetian theory of cognitive development. Each theoretical inquiry is committed to a constructivist position that supports the notion that children possess intuitive ideas about natural phenomena.

Children's Construction of Naive Theories

Studies focused on children's construction of naive theories essentially adopt a conceptual approach to the learning of science. They investigate children's specific scientific ideas, as opposed to Piaget's interest in the general mental logic of children's reasoning. While the Piagetian tradition attempted to identify generalized "content independent" forms of thinking or operational knowledge, this research inquiry focused on children's personal construction of meanings and the many informal theories that individuals develop about natural phenomena based on their personal interactions with physical events in their daily lives (e.g., concepts such as buoyancy, heat, force or motion). Virtually all this empirical work stems from a "constructivist epistemology" (Carey, 1985; Driver & Erickson, 1983; Meyer & Woodruff, 1995; Watson & Konicek, 1990) in which it is assumed that learners actively generate meaning from experience.

Over the past twenty years a rich body of empirical research has surfaced as a result of documenting children's "deviant" patterns of reasoning and problem solving in science. These patterns of thought were often described as *"misconceptions," "intuitive theories"* or *"naive theories"* (Carey, 1985; diSessa, 1988; Driver, 1985; McCloskey, 1983). Conversely, many researchers argued that learners' beliefs appear to be more piecemeal than what could be considered as cohesive theories that can be restructured through environmental mediation. For example, diSessa (1988) reported that physics students, in particular, possess "intuitive physics" or a fragmented collection of ideas loosely connected that constitute a series of "independent layers of understandability" (p.55). From Marton's (1976) perspective, these students lack any deep-level approach to understanding the physical world. Marton maintained that students are functioning at a surface-level as portrayed by their efforts to find the correct formula that solves different scientific problems. Investigation of high school and college students' performance on problems in physics revealed that misunderstandings persist in spite of their successful completion of courses (McCloskey, 1983).

As a result of these findings, an increased interest has emerged in finding ways of maintaining a happy "marriage of mutual understanding" between children's common sense understanding of scientific phenomena and formal scientific knowledge. According to diSessa (1988), "knowledge fragments" that are characteristic of students' thinking provide the basic material to develop scientific understanding, the intention being to "build a new and deeper systematicity" (p. 62) in order to integrate these pieces of knowledge. From an instructional viewpoint, the teacher attempts to remain within the parameters of the student's level of conceptualization so that discussion revolves around what is already known. Children's knowledge of and explanations for specific scientific phenomena are respected while at the same time questioned to lead children to discover gaps in their understanding (Forman,1989). These actual representations held by the child help teachers see the full context of the child's "naive" theories.

Researchers who have adopted a conceptual-change perspective (Carey, 1985; Chi,

1992) believe that the construction and revision of theories constitute the heart of cognitive development. If this is the case, then psychologists will need to know more about how the process of theory revision occurs. Strike and Posner (1985) argued that for genuine conceptual change to occur, that is, for students to replace earlier understandings with new ones, it is important that students not only recognize that they have alternative beliefs but also that they become dissatisfied with their old ones. In addition, students need to *understand* new conceptions and accept them as more plausible than their original ones. The successful science curriculum should involve students in making difficult conceptual changes. In summary, making students aware of the process of conceptual change may contribute to their achievement of it (Kuhn, Schauble & Garcia-Mila, 1992; Ruffman, Perner, Olson & Doherty, 1993; Watson & Konicek, 1990).

At the same time that the theory-based view of cognitive development was being developed, an alternate approach was also being created in the form of a learning framework model for investigating children's development. This group of investigators became interested in the way in which the representation of knowledge specific to particular content domains differed between "novices" and "experts" (Simon & Simon, 1978). The notion that "experts" in a field of knowledge analyze problems at a deeper conceptual level than do "novices" as a result of having more relevant conceptual knowledge characterizes a second inquiry known as the novice-expert shift.

The New Learning Theory: Novice-Expert Shift

The novice-expert inquiry originated from the need to replace computational models of mind based on memory structures and general processes with models based on specialized knowledge (Pozo & Carretero, 1992). This movement towards the specific led to studies investigating the importance of domain-specific knowledge in the areas of scientific reasoning and problem-solving (Chi, Glaser & Rees, 1982). There was a shift from the logical, syntactic nature of cognition (e.g., Piaget) to mental models of a more semantic nature. In the context of this learning framework, researchers have attempted to describe differences in novices' and experts' conceptual systems in the following areas: (1) conceptual knowledge of a concept (2) how knowledge is structured and organized, (3) mental representations of a problem and (4) the efficiency of problem-solving strategies. These four areas of conceptual development were chosen strictly for the purpose of improving science instruction. The intention was to provide educators with a descriptive analysis of how learning evolves from the perspective of the learner and hence avoid the current problem of the mismatch between a learner's conceptual level of understanding and instructional methods.

The nature of this research inquiry is both domain- and task-specific, emphasizing specific developments within a single content domain as opposed to general or transdomain developmental similarities in children's cognitive growth which was the main focus of Piaget's research. Furthermore, novice-expert studies have examined the differences between the problem-solving processes of "novices" and "experts" in specific areas of science such as mechanics or acceleration. Theorists in this field of study argued that a child may function at a higher level in one content area than in another if he or she has acquired expertise in that area through extensive practice and experience (e.g., Chi & Glaser, 1988). Research in the novice-expert approach to cognitive development essentially analyzed the structural reorganizations in children's and adult's knowledge networks as they acquired a higher level of understanding in a specific area (Chi & Rees, 1983; Pozo & Carretero, 1992). This second group of researchers was in agreement with the theory-based theorists in suggesting (a) that one of the key factors in children's development is the change that takes place in the structure of their conceptual knowledge, and (b) that this change takes place in a specific area or domain of knowledge and **not** across the entire cognitive system (Chi,1988; Chi & Rees,1983).

Children's scientific knowledge has been observed to undergo some changes that parallel the novice to expert shift and so this research inquiry focused particularly on the transition from novice to expert for instructional purposes. In fact, the notion of a novice-expert continuum rallied the interest of educational and developmental psychologists. They viewed the novice-expert transition as a good model for describing ways in which children's scientific knowledge changes with age (Chi & Rees, 1983). There was general consensus that as children acquire more experience in a particular domain, they begin to form new relations among the basic concepts which comprise the domain. These relations may be either conceptual or procedural in nature and gradually lead to the integration of knowledge structures that were previously distinct from each other (Chi, 1988). Once integrated, these new knowledge structures enabled learners to approach problems or confront tasks with new and more efficient strategies. For example, Larkin (1983) described how novices (i.e., beginners) tended to first represent mechanical problems in terms of familiar objects and then proceed to envision events in a temporal sequence; event 1 occurs, then event 2 and so on. On the other hand, experts adopted a "Physical Representation" of the problem based on concepts such as force, energy and acceleration.

The novice-expert shift is argued to be related to the way concepts are encoded, experts using more sophisticated codes that represent the important structures of the phenomena without overloading processing capacity. Furthermore, experts seem to differ from novices in the personal theories they use to interpret scientific phenomena. In other words, there is a considerable difference in the way the two groups represent and solve a scientific problem. From this perspective, it is expertise, not age, which explains conceptual change.

Piagetian and neo-Piagetian Theory

Whereas Piagetian theory tended to paint a picture of children's cognitive development from a general perspective, a number of neo-Piagetian theories emerged during the early 1980s with the intention of introducing a stronger set of assumptions about the specificity of children's cognitive structures and their environmental dependence. According to Piagetian theory, children's understanding of scientific concepts is analyzed from a *structural* perspective. Piaget's underlying quest was essentially epistemological. The focus of his research was on how individuals make sense of their physical world through the development of content independent logical structures and operations. This is in contrast to the other theoretical traditions in which children's scientific reasoning was analyzed from a conceptual approach. Within the context of Piaget's theory, the main goal of science educators would be in fostering structural change in children's general logical reasoning skills and in facilitating the acquisition of formal operations (Piaget, 1975, as cited in Pozo & Carretero, 1992). Instead of emphasizing a conceptual understanding of specific content, the classical Piagetian model suggests the fostering of general scientific procedures (e.g., control of variables, or proportional reasoning) whose development would allow for more complex levels of scientific thought.

However, Piaget's notion of mental logic has encountered a number of difficulties. One problem, in particular, arises from attempts to describe the nature of children's reasoning in terms of psycho-logic or logic-like mental activities. In other words, Piaget's argument that human reasoning depends on mental logic (i.e., concrete or formal operational thinking) may simply not provide a true or complete representation of the actual processes children use when explaining scientific phenomena. Current research (Case, 1985; Fischer, 1980; Halford, 1992) now suggests that those aspects of thought once conceptualized by Piaget in terms of logical structures and operations are probably better treated in terms of mental models and the operations performed on them.

Therefore, the incentive to theorize about mental models stemmed from these difficulties with Piaget's notion of mental logic and from research indicating that the way concepts are understood in real life called for a representational system with an emphasis on semantic content. The two groups of investigators, naive theorists and novice-expert theorists, reached a general consensus that children's representations of scientific concepts are dynamic rather than static since recoding and reorganization of information is not only an important component of understanding but is also central to cognitive development (Carey, 1985; Halford, 1993).

A neo-Piagetian approach was introduced to address the domain-general versus the domain-specific question which daunts most cognitive developmental research. Its attempt was to retain a general-systems perspective, but also introduce a stronger set of assumptions concerning the specificity of children's conceptual learning and its environmental dependence (Biggs & Collis, 1982; Case, 1978,1985; Fischer, 1980; Fischer & Canfield, 1986; Halford, 1982). Within this tradition, there is a strong commitment to the notion that cognitive development includes processes that are general and stage-like, as well as those that are domain-, task-, and content-specific.

Case and his colleagues proposed that children's conceptual understanding in various domains such as social, spatial and numerative follows a similar developmental sequence that progresses through hierarchically ordered major stage changes as well as minor substage shifts (Case, 1985, 1992; Dennis, 1987; Griffin, 1992; McKeough, 1992). Like Piaget, Case (1985) postulated four main stages of development from birth to adulthood. Development within each of the major stages "recycles" in a recursive fashion in the sense that the same pattern of structural changes in children's conceptual understanding is repeated. Case (1985, 1992) hypothesized four recursive cycles in children's cognitive development and this precise structural parallel within each of the stages is illustrated in **Appendix A** which represents his neo-Piagetian model of intellectual development.

Case (1996) suggested that the reason for such similarities in the general underlying structural progression across different domains may be a joint function of several general factors. These include (a) general maturational constraints on children's conceptual progress during childhood development, (b) exposure to similar cultural and school experiences and (c) common motivational factors in terms of children's natural curiosity and desire for mastery. In order to gain a better understanding and a more complete picture of the nature and development of children's conceptual knowledge, cognitive developmentalists began to adopt the concept of mental models as accounts of children's representational thinking in a number of domains relevant to school learning.

Mental Models

The development of cognitive models has provided researchers with a rigorous explanation of what it means to understand something (Case, 1992; Chapman,1990; Fischer,1980; Halford,1993). For instance, Halford (1993) claimed that it is more useful to identify the mental model that a child has of a concept than to simply categorize the child as understanding or not understanding. He suggests that "to understand a concept entails having an internal, cognitive representation or mental model that reflects the structure of that concept" (p. 7). Halford (1993) further proposes that "mental models are defined as representations that are active while solving a particular problem and provide the workspace for inference and mental operations" (p. 69). For the purpose of this study, Halford's definition of *mental models* will be used because it provides an appropriate framework in which to investigate children's scientific reasoning. Furthermore, the ontogenesis of conceptual change in scientific thinking can be monitored through the developmental changes in a child's mental model of a specific concept before and after some type of environmental mediation.

Describing cognitive development in terms of mental models enables psychologists to reinterpret some of the major issues previously raised by contemporary theories. For example, it is often questioned whether preschool children genuinely understand concepts like conservation and classification or whether their successful performances in task situations were merely based on mechanical applications of rules (Halford, 1982,1989). The idea that human reasoning depends on mental models evolved from this debate with a growth of interest in the need for reinterpreting what is meant by the term *understanding*, particularly in the fields of math and science education. For example, studies conducted by Gelman and Gallistel (1978) indicated that children's counting was not based solely on the exercise of mechanical skills but reflected an understanding of counting principles. A common goal among neo-Piagetians is to look for constructs other than Piagetian logical structures to account for the nature of children's understanding of specific concepts (Case,1985; Halford,1982, 1989). The theory of mental models enables cognitive developmentalists to conduct a more in-depth inquiry into what it means to understand something from both a structural and conceptual perspective.

Piaget's notion that human reasoning can be described in terms of general logico-mathematical structures or a general system of logical operations played an influential role in cognitive developmental literature. According to Piaget (1950,1957), mental logic or psycho-logic plays a central role in cognitive development. His main interest was in the notion of a general intelligence, concentrating more on children's ability in "logico-mathematical operations" in their attempt to understand the natural physical world (Piaget & Inhelder, 1942/1974).

Over the past several decades, theories of cognition and cognitive development have had persistent difficulties in accounting for human reasoning in terms of logical rules and principles. This concept of psycho-logic has encountered a number of difficulties in recent research. One problem in particular has been defining such a construct that convincingly captures the nature of human reasoning. Although sophisticated attempts have been made (Braine,1978; Osherson,1975, 1976), including Piaget himself (1947-1950, 1957), very little consensus about the nature of human reasoning was reached. Most of Piaget's studies were experimental in design requiring students to perform formal tasks. Piagetian conservation and perception tasks were criticized by Bruner (1986) and Donaldson (1978) as being too contrived. According to Donaldson (1979), such formal tasks limit thinking skills due to the emphasis they place on disembedded thought and language. She claims there is a disparity between children's skills as thinkers in everyday situations and those in formal experimental tasks.

Furthermore, recent research (Carey & Smith, 1993; Case, 1992; Driver, 1994) is coming to the realization that, in problem-solving tasks, not only does the logical structure of the problem have an influence on how the problem is approached but also the content of the problem. As will hopefully have been apparent, the various theories that have been previously introduced (i.e., naive, novice-expert and neo-Piagetian) suggest that cognitive structures should be viewed as semantic not logical in nature (Carey, 1985; Case, 1992; Chi, Glaser & Rees, 1982; Halford, 1993). Empirical data from studies conducted within each of these inquiries indicate that children have everyday representations or mental models of their physical world. These representations are content-specific in the sense that they consist of specific examples rather than logical principles.

The following two examples provide support for the notion that children's reasoning relies heavily upon domain-specific knowledge which, in turn, suggests that representations of concepts are more content-specific than Piaget previously believed. Tversky and Kahneman (1973, cited in Halford, 1993) reported that "natural reasoning mechanisms depend heavily on retrieval of information from memory rather than on the application of logical rules" (p.22). Secondly, McCloskey (1983) found that high school students understood the concept of motion in a way that was experience-based rather than logical. Therefore, it seems that the way concepts are represented mentally differs from the previously accepted Piagetian logical-mathematical structures of mind. As a result of these findings, different theories were developed that utilized the concept of mental models to attempt to define the nature of children's understanding about specific concepts.

In summary, a mental model comprises the representation that is currently active about a specific problem or concept. In other words, mental models are representations or constructed schemes of thought that are active while solving a particular problem and concomitantly provide the workspace for inference and mental operations (Halford, 1993). Mental models are not purely syntactic as was the case with psycho-logic models; they also include semantic information. They are content-specific representations rather than logical principles. Representations are dynamic rather than static, since reorganization of information is an important component of understanding. They change dynamically as learning, concept attainment and problem solving proceed.

From a neo-Piagetian perspective, cognitive development depends on knowledge acquisition and conceptual restructuring. Recent work on children's thinking shows that prior knowledge and understanding play a central role in children's development of scientific reasoning and knowledge (diSessa, 1988; Kuhn, Schauble & Garcia-Mila, 1992; Reif & Allen, 1992; Ruffman, Perner, Olson & Doherty, 1993). These studies articulate relations between the domain-specific theories or beliefs children hold and the ways they generate and interpret evidence. The "naive" theories that children develop about natural phenomena (Carey, 1985; Driver, 1985) result from their personal interactions with physical events in their daily lives (Piaget, 1970). Therefore, the importance of social and environmental factors also need to be addressed because knowledge depends on interaction with the environment.

There are two major traditions in explaining the process of acquiring scientific knowledge: individual and social constructivism. The foregoing research inquiries (naive theory, novice-expert shift, neo-Piagetian) specifically focus on children's personal construction of meanings and the many naive theories children develop about different scientific phenomena. These inquiries were interested in the mental activities of the learner based on personal interactions with physical events in their everyday lives (Carey, 1985; Case, 1985, 1992; Chi, Glaser & Rees, 1983; Driver, Guesne & Tiberghien, 1985). At the same time as these inquiries were being implemented, another group of investigators decided to take an alternate position and study children's knowledge acquisition within social, cultural and physical contexts.

In a social constructivist framework, communication and instruction through social interaction are recognized as important processes in the development of children's scientific learning. The unit of analysis in this research inquiry is the "individual-in-social-action" (Rogoff, 1990; Vygotsky, 1978). Social constructivists' intention was to move beyond a psychological, individualistic constructivist approach and adopt a more sociocultural view of children's learning while still maintaining a constructivist epistemology regarding cognitive development. From a social constructivist viewpoint, therefore, the issue is that of explaining how participation in social interactions and culturally organized activities influences children's cognitive development.

Social Constructivism in Science Education

One of the core postulates of Halford's (1993) theory is that active experience is required for conceptual development. Concepts are not acquired solely by instruction. Social input must be related to a child's own representations to make sense (Halford, 1993). Many concepts children acquire are instantiated in the environment. For example, the concept of density is built upon young children's experience with placing objects in water to see if they float or sink. Thus the concept of buoyancy provides the initial building blocks or the critical link to an understanding of density.

Concept of buoyancy. The buoyancy of an object is a property that can be perceived clearly. Since density (mass per unit of volume) is one of the factors that determines an object's buoyancy, it is plausible to think that young children may have some implicit knowledge of density. Young children's understanding of density can be characterized by its directly perceived experience-based sense (e.g., a piece of balsa wood and a lead weight) while older children and adults may conceptualize density in terms of its mathematical formulation (mass per unit of volume). These two levels of conceptual understanding represent implicit and explicit knowledge of the concept, respectively; the latter representations are cognitively accessible to the rules or knowledge utilized in developing an understanding while the former are not. The developmental importance of these two conceptualizations lies partly in the fact that young children's implicit knowledge of density has not yet surfaced at the explicit level. An educator's goal therefore is to promote this transition from an implicit to an explicit level of understanding.

Social constructivists believe that the process of knowledge construction must go beyond personal empirical inquiry. They believe that children's cognitive development is dependent on the linguistic and conceptual frameworks (i.e., mental models) that they inherit from their culture and on the physical and social technology with which these frameworks are associated. Their main area of interest is in the different kinds of interactive processes that introduce children to the conventional science ideas or to the scientific ways of knowing. The learning of concepts, models and conventions of the scientific community is knowledge that cannot be discovered by themselves. For instance, Vygotsky (1978) emphasized the importance of social interaction with more knowledgeable others. From this perspective, scientific knowledge and understandings are constructed when individuals engage in talk and activity while working with others on specific problem-solving tasks.

Contemporary researchers in the field of science education have investigated the effects of a generative teaching model on the development of children's scientific knowledge (Bloom,1995; Woodruff & Meyer,1994,1995). In this model, groups of students work together as collaborative cohorts in a consensus-building process that involves meaning-making conversations while engaged in scientific inquiry. Their goal is to reach a group explanation for and a mutual understanding of the particular subject matter under investigation. Examining student's discourse provides opportunities for educational researchers to delineate the social and individual dynamics of children's thinking and how this interchange of ideas contributes to the construction of meaningful understandings. As a result, case studies of conversational analyses of students' scientific discourse have become a popular research strategy (e.g., Bloom, 1995; Driver, Guesne & Tiberghien, 1985; MacDonald & Kass, 1995; Pea, 1993; Woodruff & Meyer, 1994, 1995).

Other researchers working within a social constructivist framework are interested in studying the ways in which students' common sense understanding of physical phenomena is drawn upon and interacts with classroom instruction on the conventions of science (Johnston & Driver, 1990; Watson & Konicek,1990). From an instructional viewpoint, Case (1992, 1996) suggests that educators need to first assess children's current representation or mental model of the task domain in question and identify any misconceptions resulting from their conceptual understanding. From this knowledge base, Case proposes developing curricula that take such naive theories into account and challenge children to take an active role in changing them. A strong social component features in Case's neo-Piagetian model as one of the underlying processes on which the acquisition of children's conceptual structures depend.

Relevance of Developmental Theory to the Field of Education

Over the last two decades, educational researchers have taken a view of conceptual development that was less monolithic than Piaget had proposed. For instance, contemporary theorists are now in general agreement that children's conceptual development is less dependent on the emergence of general logical structures than Piaget had suggested and more dependent on the acquisition of knowledge and skills that are domain, task, and context specific. More specifically, they now believe that one of the most important changes in children's development is the change that takes place in the structure of their conceptual knowledge and that this change takes place in a fashion that is not general to the entire cognitive system but is domain-specific. In addition, investigators took on the view that children's thought is more responsive to external influence than Piaget had thought and more dependent on the social interaction that had been described by Vygostsky (1978).

The nature and development of children's scientific thinking as accounts of their personal construction and revision of naive theories about the physical world has provided teachers with a better understanding of how children learn and make sense of their physical world (Carey,1985; Driver et al., 1985). In addition, empirical data from the information-processing approach that analyzed the differences between the structural and conceptual knowledge of "experts" and "novices" confirmed the importance of specialized knowledge (e.g., physics) in the development of students' scientific reasoning and problem-solving abilities (Chi, 1988; Chi & Rees,1983). From the social constructivist research inquiry, teachers are informed of the importance of communication and instruction through social interaction in facilitating children's scientific learning. What is lacking in this research approach is a long-term account of the developmental changes that occur in a child's mental model of a specific concept before and after some type of social intervention. Most of the studies conducted within this tradition focus on a "snap-shot" model of children's representational thinking of a scientific concept rather than a continuous monitoring model.

Clearly what educators need, particularly in the area of teaching physical sciences, is a theoretical system in the form of a developmental model of conceptual change that would be sufficiently fine-grained in terms of reflecting the structure and dynamics of children's cognitive systems. Such a model would enable educators to identify a child's existing level of conceptualization which in turn would provide the starting point upon which to build instruction that is developmentally appropriate. Bridging the gap between theory building, on the one hand, and contributing to the improvement of educational practice, on the other hand, has become more prevalent in research on learning, development and teaching. However, many research investigations have been beset with problems in how to deal with the complex issues of putting their theory into educational practice. Although they have been able to articulate certain very general principles for instructional programming, many developmental theorists have been unable to design an explicit developmentally-based instructional model for teaching specific subject matter.

Combining theory-oriented inquiry and research aiming to improve instruction has been a major goal of neo-Piagetian theory. Within this neo-Piagetian tradition, Case (1985, 1992) designed both developmental and instructional models that have several practical implications for educators. The developmental model enables educational researchers to conduct a detailed analysis of the structural and conceptual changes that occur in children's representation of knowledge in different domains at various points in their development. In so doing, it is now possible for educators to (1) assess children's "entering competence" in a specific topic and then (2) set developmentally realistic goals.

The processes by which children construct meaning have obvious importance with regard to how science should be taught. Case and his colleagues have designed an instructional methodology that serves as an adjunct to his developmental model. It has enabled teachers to plan a more effective set of intervention strategies that advances children's conceptual understanding (Case & Griffin, 1990; Case, Sandieson & Dennis, 1986). It is important for teachers to understand learning from the perspective of a learner and then design instruction accordingly based on that same perspective.

Objective of the Study

The objective of this study was to investigate the nature and development of children's understanding of scientific phenomena in middle childhood. More specifically, the purpose of this research was to determine whether or not there was a developmental sequence in children's understanding of buoyancy across the ages of 6, 8, and 10 years. Using Case's (1985, 1992) developmental model as a theoretical framework, my intention was to chart both the conceptual and structural development of children's representations of buoyancy across these three age groups. The main goal was to determine whether or not children's conceptual levels of understanding change systematically with age in a progressive and hierarchical manner consistent with the age-level postulates of Case's model. From an educational perspective, the question is not so much about the "true age" at which a formal understanding of the concept is acquired, but about what aspects of the concept develop at different ages (Kohn, 1993).

Significance of the Study

Although recent research in developmental psychology is providing more insight into the nature of children's scientific knowledge and into the enigma of conceptual change, what is becoming most apparent is the need for more empirical data on children's conceptual development of scientific concepts. Experimental tasks need to be designed that are more naturalistic and less contrived. In particular, studies need to be conducted within a theoretical framework that charts the development of children's conceptions of a specific scientific concept at different ages. This will help to determine whether an underlying natural progression exists over time. Furthermore, the identification of common patterns of scientific thought generated by children of similar ages provides insight into how children intuitively approach a problem or construct a conceptual understanding. Such information also provides a basis for the "optimal match" (Donaldson, 1978) between learner and the curriculum. Understanding the developmental progression of a scientific concept such as buoyancy will facilitate planning for effective instruction particularly in the challenging area of the physical sciences. Developmental research conducted within the conceptual framework of Case's neo-Piagetian theory of cognitive development can provide insight into the nature and development of children's scientific knowledge and into the enigma of conceptual change.

Rationale for Case's neo-Piagetian Model

Case's (1985, 1992) neo-Piagetian model provides a solid theoretical foundation that enables researchers to combine previous theories into one solid framework. It is a flexible framework that enables researchers to combine structural and conceptual analyses into one paradigm. The validity of this model has already been established in previous studies that have identified a general progression in children's scientific and mathematical thought (Case, Sandieson & Dennis,1986; Griffin, Case & Sandieson, 1992; Marini, 1984, 1992). Although the surface elements or content in a specific domain or subject may be quite different, the underlying progression is virtually identical. For instance, increasing evidence from neo-Piagetian studies supports the notion that children's cognitive development progresses through or can be encapsulated in a recurring dialectical cycle of structural complexity (Case & Okamoto, 1996). Subsequently, this neo-Piagetian model has the potential to chart age-typical patterns of children's scientific reasoning about buoyancy.

Piagetian theory analyzed children's understanding of scientific concepts from a *structural* perspective, investigating the general logic of the child and the causal explanations he/she gives. Neo-Piagetian theory maintains a structural approach but adds semantic and syntactic information, thus providing a more complete picture of children's understanding of scientific concepts. Furthermore, Case's (1985, 1992) theory provides a metric for classifying the developmental level of conceptual operations in terms of their complexity. This enables researchers to articulate the nature of children's representations of knowledge in different domains at various points in their development.

The implications of neo-Piagetian theory for science education will be considered in Chapter 2. Particular reference is made regarding the utility of Case's perspective to chart the development of children's understanding of buoyancy and to inform instructional design. The chapter begins with a review of the literature on mental models for its contribution to understanding conceptual change in children's representational thinking of scientific phenomena. Following this, a review of different research inquiries which utilize mental models to articulate children's scientific understanding will be examined. The strengths and limitations of each theory's contribution to furthering educators' understanding of the development of children's understanding of scientific phenomena and to improving instructional methods is summarized at the end of each review. Throughout the chapter a strong argument will be built regarding the educational relevance of neo-Piagetian theory in the field of science education.

CHAPTER 2 : REVIEW OF LITERATURE

Introduction

Although recent research in developmental psychology is providing insight into the nature of children's scientific knowledge and into the enigma of conceptual change (Carey & Smith, 1993; Driver, 1985, 1994; Reif & Allen, 1992; Watson & Konicek, 1990) what is becoming most apparent is the need for more empirical data on both the structural and conceptual nature of the changes that take place in the learning of science, for the specific purpose of improving the teaching of science. Conceptual change in scientific thinking refers to the way children reorganize and restructure their knowledge about a specific concept (e.g., buoyancy) as they acquire a more sophisticated conceptual understanding over time. Current debates about conceptual development have focused on what changes over time and what stays the same.

There is a consensus among some cognitive psychologists (Carey, 1988; Case & Okamoto, 1996; Fodor, 1982; Karmiloff-Smith, 1996; Kohn, 1993) that children appear to come into the world well prepared to process different domains of knowledge (e.g., social, physical sciences, number). Although young children may not have fully fleshed-out concepts within these general domains in the early stages of their development, they appear to demonstrate implicit or innate understandings, in other words, conceptual underpinnings upon which later formal concepts may be built (Gelman & Baillargeon, 1983). Spelke (1988, 1991) took the view that change was a constant process. She believed that physical reasoning and object perception in infancy do not undergo radical changes but develop through enrichment processes around a certain core of principles. From a different viewpoint, children may come equipped with the ability to understand weight, volume and density but over the course of development may still need to sort out their knowledge through experience of which properties are most relevant in particular situations.

This enigma of conceptual change has daunted researchers for decades. For instance, the underlying mechanisms that induce structural changes in a child's knowledge representation (i.e., the way information is conceptualized) still remain a mystery. A review of the literature revealed that there were many studies that described children's development of different scientific concepts (Carey, 1985; diSessa, 1988; Driver, 1985 ; Kohn, 1993; Marini, 1992) but there was an apparent lack of studies explaining how that development comes about. As Susan Carey (1990) commented, one obvious reason for this is that psychologists cannot begin to explain developmental changes until they know what they are. From an educational perspective, the type of content and patterns of thought generated by children regarding a specific concept can provide insight into how children intuitively approach a problem or construct a conceptual understanding (Case & McKeough, 1990; Case, Sandieson & Dennis, 1986). Therefore, theories that are best suited for educational purposes are those that focus on why and how children's conceptions change.

The notion that children have mental models or intuitive ideas about specific phenomena provides researchers with a theoretical framework to monitor development and change in children's conceptual understanding of a specific scientific concept. One of the major objectives of this chapter is to define what is meant by the term **mental models** and to examine the architecture of such a construct. The term *mental models* is one of many different constructs that have been used in the developmental literature to describe children's representational thought regarding specific phenomena. The mental models of interest in this study are children's conceptual representations of scientific concepts, specifically buoyancy. The literature on mental models is reviewed subsequently for its contribution to understanding conceptual changes in children's scientific understanding.

Outline of Chapter

The presentation of the literature review for this chapter is organized into three sections: (1) the architecture of mental models, (2) theories utilizing the concept of mental models to investigate the nature and development of children's scientific thinking, (3) neo-Piagetian theory and its applications to science instruction.

The first section of this chapter begins with a detailed discussion of the architecture of mental models in terms of representational thought. A definition of the term ***mental models*** is provided that is appropriate for investigating children's scientific reasoning. Following this, three different theoretical perspectives that utilize the construct of mental models to investigate the nature and development of children's scientific thinking are presented. They are as follows (1) cognitive development as theory development, (2) novice-expert shift: The new learning theory and (3) social constructivism. Examples of studies investigating conceptual understandings of specific physical concepts will be summarized according to the type of research methodology used. A particular focus on studies investigating children's understanding of physics, with an emphasis on children's understanding of density will be considered. At the end of this second section the similarities and differences in theoretical viewpoints are summarized.

The third section introduces a fourth research inquiry, namely neo-Piagetian theory, which provides the theoretical framework for this research project. As the name implies, this group of researchers share Piaget's view of development but, in addressing some of the problems regarding the application of Piaget's theory to educational practices, neo-Piagetians have drawn on other theoretical approaches, particularly the information-processing approach. Since all four theoretical approaches incorporate the concept of mental models into their research inquiries, the following section will take a brief historical look at how the notion of mental models developed and also how it has evolved from the Piagetian era to its present day use in educational research.

The Architecture of Mental Models

The Development of Mental Models

The incentive to theorize about mental models came from difficulties in describing human reasoning and accounting for cognitive development in terms of the Piagetian orientation towards mental logic. Moreover, in the last decade, there has been a surge of empirical evidence to support the notion that the way concepts are represented mentally differs from the previously accepted Piagetian logical-mathematical structures of mind (Carey, 1985, 1991; Case, 1985, 1992; Fischer, 1980; Flavell, 1988). For instance, Driver (1994) found that elementary school students understood concepts such as heat or light in a way that was experienced-based rather than logical.

Piaget assumed that children's cognitive growth depends on knowledge structures that are coherent, logical and general rather than specific in nature. His underlying quest was essentially epistemological. The focus of much of his research was on how individuals make sense of the physical world through the development of content-independent logical structures and operations. Therefore, changes in scientific knowledge were essentially considered to be *structural* in nature. For example, logical tasks such as conservation of matter were supposedly dependent on the gradual emergence of a general operational structure (e.g., concrete or formal). Piaget believed that children's representations of scientific phenomena were determined by a number of general logical structures, whose development would allow for more complex levels of thought (Flavell, 1982). Structural change was considered to be general in nature and characterized by qualitatively distinct cognitive operations (i.e., concrete versus formal thinking) that were independent from and uninfluenced by specific content (Piaget, 1972).

Conversely, cognitive developmental literature over the last two decades has given new emphasis to the importance of domain-specific knowledge (e.g., Carey, 1985; Carey & Smith, 1993; Chi, 1988; Chi & Rees, 1983; Driver, 1994; Wellman, 1990). For instance, this group of theorists was interested in cognitive structures that are specific to particular content domains such as physics, chemistry, or chess. There is a growing recognition that prior knowledge and its interaction with new incoming information play a central role in children's development of scientific reasoning and in their acquisition of scientific and mathematical concepts (Carey, 1985; Chi & Ceci, 1987; diSessa, 1988; Kuhn, Schauble, & Garcia, 1992; Reif & Allen, 1992; Ruffman, Perner, Olson & Doherty, 1993). Hence, investigators began to articulate a view of cognitive development that was far more local than Piaget had described. They perceived children's development as more domain-, task-, and context-specific (e.g., Carey, 1985; Carey & Smith, 1993; Case, 1985, 1992; Fischer & Pipp, 1984). Furthermore, changes in children's thought appeared to be more responsive to external influences and dependent on the sort of social interaction that Vygotsky (1962) described.

One way that current mental models differ from Piaget's "psycho-logic" is that they contain more semantic information. Mental models may comprise logical characteristics but they are essentially content-specific representations depending on domain knowledge. For example, Case (1992), a neo-Piagetian, proposed that cognitive structures are "organized sets of concepts and conceptual relations" (p. 130) applicable to a broad range of content that is domain-specific. According to the neo-Piagetian view, children develop concepts, control structures and skills in quite a local fashion (Case, 1985; Fischer, 1980). In fact, children's logic appears to be more content-dependent than Piaget had thought.

Many scientific reasoning problems are often undertaken by retrieval of content knowledge acquired through experience. Recall, for example, McCloskey (1983) who found that his high school students understood the concept of motion in a way that was experience-based rather than logical. Hence, it seems that the way concepts are understood calls for a representational system that emphasizes semantic information. There is now substantial empirical data supporting the notion that children's cognitive growth is more content-dependent than Piaget had conceptualized (Carey, 1990; Carey & Smith, 1993; Case, 1992,1995; Case, & Okamoto, 1996; Driver, Asoko, Leach, Mortimer & Scott, 1994; Kuhn, 1989; Reif & Allen, 1992).

The development of mental models has enabled researchers to gain a better understanding of the cognitive underpinnings on which children's scientific reasoning depends. In recent studies that administered more applied tasks in science (e.g., solving physics problems), it became apparent that student performance was at least as dependent on specific knowledge as it was on general problem solving heuristics (Carey & Smith, 1993; diSessa,1988; Kuhn, Schauble & Garcia-Mila,1992; Reif & Allen, 1992). Although most of this research focuses on domain-specific knowledge rather than general reasoning schemes, Piaget's central concern, it shares a number of commonalities with the Piagetian viewpoint and can lead to similar perspectives on the teaching of science. Both view meaning as being made by the individual and assert that meaning depends on the individual's current mental model articulated in terms of knowledge schemes that represent an internal network of cognitive structures reflecting concepts and conceptual relations. The two approaches differ regarding the nature of mechanisms that induce conceptual change.

In Piaget's account of cognitive development, conceptual change occurs through periodic restructuring of children's general logical operational structures. Conversely, current theorists articulate a view of cognitive development far more local or domain-specific than Piaget described (Carey, 1985,1988; Case,1985, 1992; Fischer,1980; Halford,1993). Conceptual change from this viewpoint entails the reorganization and restructuring of children's conceptual knowledge of a specific topic. As a result of these two different viewpoints, the theory of *mental models* was developed to paint a more complete picture of children's representational thought regarding specific phenomena (Astington,1994; Carey,1985; Griffin, Case, & Siegler,1994; Driver,1985; Wellman,1992).

Cognitive development in terms of mental models enables psychologists to investigate both the general and specific features of children's cognition. One of the major objectives of this chapter is to define what is meant by the term *mental models* and to examine the architecture of such a construct. The following section is devoted to the concept of mental models.

The Nature of Mental Models

As previously mentioned, the term *mental models* is one of many different constructs that have been used in the developmental literature to describe children's or adults' interpretations of everyday natural phenomena. More specifically, a mental model is a cognitive representation that has been personally constructed about a specific problem or concept. Other terms that are essentially considered synonymous to the construct of mental models are: intuitive ideas, naive theories, conceptual frameworks, knowledge networks, schemata or cognitive structures. In a general sense they may be considered broadly equivalent as they refer to children's representational thinking about their physical world. However, a close examination of the developmental research conducted within the field of science education reveals some subtly different connotations in meaning. For example, terms such as 'intuitive' or 'naive' emphasize the origins of children's ideas whereas terms such as 'theories,' 'frameworks' or 'structures' suggest the mental organization or constructed schemes of children's ideas and the relationships between them.

Furthermore, in 1985, Gilbert and Swift developed a new research program for science education termed the "Alternative Conceptions Movement." Within this line of investigation in the field of science teaching, researchers coined the term "alternative conceptions" to describe children's mental models to emphasize the difference between children's intuitive ideas and formal scientific knowledge. Despite the emergence of a plurality of terms used in both fields of research, the term mental models and all its counterparts refer to cognitive representations that children construct about natural phenomena in their everyday world. Generally speaking, a mental model refers to all the knowledge an individual brings to bear upon a specific concept, problem or event. There are certain preconditions for the construction of mental models :

(1) Knowledge is acquired as a result of everyday experiences, through practical physical activities, social interaction and instruction.

(2) Individuals are constructive thinkers who actively select and interpret environmental information as they construct meaningful knowledge in a scheme of accommodation and assimilation (Piaget, 1972).

(3) These constructed schemes of thought are stored in memory in various forms according to an individual's interpretation.

Hence, learning takes place through the interaction between a learner's experiences on the one hand, and on the other, the mental models (s)he uses to interpret and give meaning to those experiences.

Maintaining a "constructivist epistemology" (Driver, 1982), *mental models* are children's personal constructions of the physical world. These personal constructions are the end product of complex interactions among the sensory system, the environment that supplies the sensory information and the cognitive structures through which this information is organized to form an internal model of the outside world (Strauss, 1981). Moreover, these personal constructions can influence the manner in which information is acquired. Researchers who have investigated children's science learning have discovered that this cognitive process of interpreting phenomena reflects the way in which scientific knowledge is generated (Carey, 1985; diSessa, 1988; Driver, Guesne & Tiberghien, 1985; Smith, Carey & Wiser, 1985; Watson & Konicek, 1990).

For example, the results of studies conducted by Smith et al. (1985) led the authors to suggest that the development of children's understanding of the concepts of weight, volume and density may parallel the historic development of these concepts in the science discipline itself. In other words, students' learning in science may reflect similar patterns of change as have occurred in the development of scientific knowledge, through progressive restructuring of their own underlying theories.

In a slightly different vein, developmental psychologists often coin the term *mental models* as a theoretical framework for the specific purpose of describing the nature and development of children's conceptual understanding of specific phenomena. Cognitive development in terms of mental models enables psychologists to investigate both the general and specific features of children's cognition. Furthermore, researchers are able to articulate both conceptual and structural aspects of children's scientific thinking - what children know about a given topic and how they structure or integrate this knowledge in a meaningful way that makes sense to them.

Over the course of development children's mental models of a specific concept undergo many conceptual restructurings as new knowledge is acquired through induction and experience. Therefore, given that mental models are cognitive representations and representations are the workspace of reasoning and developing an understanding, the first task is to describe the nature of these cognitive representational systems.

Mental Models as Cognitive Representations

The information-processing approach was once a main strategy for the study of cognitive development. It conceived of the human mind as a complex computer-like system. Like a computer, the cognitive system manipulates or processes information coming in from the environment or already stored in memory. This information is transformed into a *cognitive representation* of some sort which is then compared with information already in the system, assigned meaning and finally stored in memory (Siegler, 1983, 1991; Sternberg,1989).

Neo-Piagetians articulate cognitive representations in terms of conceptual structures. They proposed that children's structures be viewed as sets of specific schemes or blueprints that consist of meanings, representations or concepts that children assign to everyday natural phenomena. For instance, a cognitive representation, defined by Halford (1993), is "an internal structure that mirrors a segment of the environment," (p. 69). A simple example of a structure would be an ordered set, such as {pebble, balsa wood, feather} ordered according to weight. It consists of three elements (pebble, balsa wood and feather) and the relation "heavier than" between the elements pebble and balsa wood, between balsa wood and feather and between pebble and feather. A set of elements linked by one or more relations constitutes a structure (Halford,1993). This interpretation of a mental model corresponds to the definition provided by Case (1985). He proposes that cognitive structures are "organized sets of concepts and conceptual relations" applicable to a broad range of content that is domain-specific. A cognitive structure or representation may reflect any aspect of the world with which the individual interacts.

Fischer (1980) cautions researchers about the meaning of representation. He claims that the term is often used synonymously with recall memory or symbol use. A single representation is defined by its structure not by its function as recall. Furthermore, Halford (1993) strongly insists that representations are not "pictures in the head," but "a set of cognitive processes that can be mapped onto segments of the environment in such a way that there is a structural correspondence; that is, relations in the representation must consistently correspond to relations in the segment of the environment represented" (p.239). Representations may exist in a variety of modes and the choice of representation may depend on individual differences and task demands. The most important thing is that the structure of the mental model corresponds to the structure of the concept or task that is represented.

Empirical evidence in science education literature supports the notion that two different modes of representation may coexist in children's mental models of a scientific concept, perceptual and conceptual representations (diSessa, 1981, 1988 ; Driver, Guesne & Tiberghien, 1985; Piaget & Inhelder,1942/1974; Watson & Konicek, 1990). For instance, a common characteristic that became apparent in Driver and her colleagues' (1985) studies of children's ideas about certain scientific phenomena (e.g., light, electricity and particulate matter) was the tendency for children and sometimes adolescents to base their reasoning on observable features in a problem situation. Hence, children's ideas or conceptions appear to be highly dependent on their perceptions. For instance, children believe that sugar 'disappears' when it dissolves rather than continuing to exist in tiny particles too small to be seen. Alternately, children believe that the existence of light means intense light (e.g., turning on a light bulb), and when light is not intense enough to be perceptible it no longer exists. Examples like these provide convincing evidence that perceptual experiences have a strong influential effect on the nature of children's mental models or conceptual structures regarding physical concepts.

Watson and Konicek (1990) go even further and argue that perception itself can often create a barrier to conceptual change in children's scientific thinking. The assumption that "seeing is believing" is often not the case in scientific knowledge as proven by the 'disappearing act' of the sugar example. In other words, children make qualitative judgments about physical concepts such as conservation of matter, temperature, or buoyancy based on intuitive ideas generated from sensory information. Researchers in the field of science education (Carey, 1985; Driver et al., 1985) also conclude that salient perceptual features such as the ones described above tend to dominate students' reasoning and govern their responses.

Strauss (1981) argues that much of our common sense knowledge is constructed from a perceptual basis and as a result of this may be considered (1) spontaneous in the sense that it is acquired without any formal instruction and (2) universal in that children may have common conceptual understandings about certain natural phenomena as a result of similar perceptual experiences. On the other hand, Strauss (1981) argues that formal scientific knowledge is not spontaneous and requires instruction before it is part of a child's conceptual repertoire.

This perceptual-conceptual distinction has been an ongoing and complex debate in cognitive psychology for many years. Since perceptual and conceptual processes are interactive components in children's scientific reasoning, a brief summary of how some theorists have differentiated perceptual and conceptual representations will follow. It is important to identify subtle differences in the nature of these two constructs despite the complexity of their inter-relatedness in the construction of cognitive representations. The following section will attempt to unravel this perplexing issue of whether perceptual and conceptual representations are part of one or two quite different constructs. Included is a description of the underlying cognitive mechanisms that clearly differentiate the two representations.

Perceptual-conceptual distinction. It has long been argued whether perceptual representations should be considered distinct from conceptual representations. For example, consider these two representations for the phenomenon of light: (1) light only exists when it produces perceptible effects such as a patch of light, as opposed to (2) light conceptualized as a form of energy which travels through space. Alternately, consider these two predictions made by children on a balance beam task (1) the side of the balance beam with the *most objects* will go down or (2) the side with the most *weight* will go down.

Piaget (1950) always claimed that perception and thought were distinct. He probably reached his decision on the basis that perception is spontaneous knowledge acquired through our sensory system, whereas thought is a cognitive process by which children construct a conceptual representation of a specific phenomenon. Bryant (1974), on the other hand, pointed out that many cognitive tasks require the interaction of both processes and due to the complex nature of the interplay of perceptual and conceptual representations she deemed the distinction unnecessary. This is an important issue in the domain of scientific reasoning since educators cannot infer conceptual competence when a task can be successfully performed by perceptual processes.

Consider, for example, children confirming that sugar dissolved in water still exists by tasting or evaporating the solution. Proof of existence by these procedures is perceptually based and does not necessarily assume a conceptual understanding of the conservation of matter under physical transformation. To be able to conceptualize that dissolved substances (e.g., sugar) still exist even though they cannot be perceived requires drawing on knowledge outside the event itself and breaking away from a perceptually dominated way of thinking to the construction of mental models involving the use of certain concepts or scientific parameters (e.g., particulate matter, conservation of matter under physical transformation). Despite changing appearances, children need to conceptualize that matter is particulate and that these component particles do not disappear but simply change their energy and form. However, it does not go without saying that with formal instruction, children may gradually learn to adopt a formal scientific conceptual representation of what actually happened.

Therefore, the first means by which perceptual and conceptual representations can be differentiated may be conceptualized as follows. Perceptions are immediate and influential in the way we conceptualize the world. Perceptual representations reflect cognitive structures based upon sensory information acquired through one's observation of the physical world. Conversely, conceptual representations are less spontaneous and require a more effortful reasoning process that entails moving away from the perceptually obvious focus of the situation to think about other less obvious aspects of the problem.

Two kinds of conceptual representations can be identified in children's scientific thinking. There are conceptual representations of a formal scientific nature which require children to use their imagination and considerable cognitive effort to describe relationships and interactions between the critical variables or elements involved in a scientific system (e.g., as in the case of the 'disappearing sugar,' particulate matter or conservation of matter under physical transformations). There are also conceptual representations reflecting children's intuitive ideas of everyday natural phenomena - mental models that have been constructed without formal science instruction. They are cognitive representations that reflect an individual's personal interpretation or conceptualization of a particular scientific concept (e.g., buoyancy) based solely on perceptual experiences. In other words children's conceptions are linked to their perceptions. Recall that this notion was Bryant's major concern regarding the inter-relatedness of the two cognitive representations.

Some theorists (Halford, 1993; Karmiloff-Smith, 1986; Mandler, 1988) support a perceptual-conceptual distinction on the grounds that conceptual knowledge is accessible at the conscious or explicit level, whereas perceptual knowledge is unconsciously or implicitly acquired. The essence of this argument is that since perception is an immediate process requiring very little cognitive processing we are often not consciously aware of utilizing this information. On the other hand, conceptual representation which is based on either intuition or learned scientific knowledge requires a conscious effort that explicitly constructs knowledge in a way that it is understood.

Following along this line of distinction, a second possible way of differentiating perceptual from conceptual representations is to describe them in terms of implicit and explicit knowledge (Karmiloff-Smith,1986). Hence, this differentiation is based on the premise that implicit and explicit knowledge correspond to perceptual and conceptual representations respectively. Karmiloff-Smith (1986) made the distinction between implicit and explicit knowledge within the context of children's conceptual development. The developmental importance of the distinction lies partly in the fact that explicit representations of knowledge are cognitively accessible whereas implicit representations are not. Evidence from infant studies suggests that representations are present at an implicit level but the capacity for understanding such representations is acquired gradually over the course of development (e.g., Astington, 1993; Flavell, 1988; Spelke, 1988; Wellman & Gelman, 1992). These cited authors investigated young children's development across a variety of domains such as numerical knowledge, object permanence, and pretend play as well as their development of a theory of mind.

According to Karmiloff-Smith (1986, 1990), explicit knowledge is acquired through "representational redescription." This refers to a process in which children create a higher level of understanding in terms of an explicit representation of knowledge that already exists in an implicit form. The implicit knowledge continues to exist but over the course of time becomes represented at a higher cognitive level that is linked to other cognitive processes. Karmiloff-Smith (as cited in Halford, 1993) argued that "implicit knowledge consists of procedures for performing a task {e.g., predicting buoyancy of objects} without cognitive access to those procedures or the ability to link them to other knowledge," (p.48). Hence, implicit knowledge implies task performance with understanding but without a linguistic explanation whereas explicit knowledge implies being able to explain one's understanding.

Empirical evidence supports the notion that children and adults vary the complexity in their cognitive functioning depending upon the situation and the type of information to be processed (Baddeley, 1990; Fischer & Pipp, 1984; Karmiloff-Smith, 1986). Karmiloff-Smith (1986) suggests at least two kinds of cognitive functioning : one that is quick, efficient and subconsciously processed and another that is slower and more effortful that processes information at the conscious level. This notion leads to the implication that there may be two different types of cognitive representation: (1) an implicit mode which is relatively effortless and (2) an explicit mode of operational thinking requiring more cognitive effort as knowledge is processed at the conscious level in an endeavor to achieve conceptual understanding. These implicit and explicit modes of cognitive representations may reflect the underlying processes responsible for producing perceptual and conceptual representations respectively. Alternately, it is quite possible that cognitive representations of scientific phenomena may reflect an interaction of these two underlying processes.

Although theorists (Driver, 1985; Halford, 1993; Karmiloff-Smith,1986) have shown ways that clearly differentiate perceptual from conceptual representations, what emerges from the literature is that the inter-relatedness of the two knowledge representations is an extremely complex process. This interplay of perceptual and conceptual representational thinking may be central to human reasoning across all domains, not just in the area of scientific reasoning. Moreover, this perceptual-conceptual interactive process may be one of the cognitive underpinnings upon which the construction of mental models is formed.

Educational Significance

Empirical evidence within the area of scientific reasoning (Carey, 1985; Driver et al., 1985) suggests that perception may initially influence the construction of conceptual representations. However, once a child has constructed a mental model about a specific concept (e.g., buoyancy), this model will generally remain stable over a period of time until another more sophisticated model is eventually substituted. A common characteristic that Driver and her colleagues (1985) identified in children's conceptual representations based on perceptual experiences is that these ideas are strongly held and resistant to change. Children will not easily surrender their carefully constructed mental models of specific phenomena. In fact, it takes a considerable amount of time and perceptual counter-evidence combined with new knowledge before conceptual change can occur. For instance, when children are confronted with perceptual evidence that contradicts existing beliefs or misconceptions, children accommodate their thinking by intellectualizing a "sensible" reason for why such a phenomenon occurred (Tschirigi, 1980). Simply perceiving such a discrepant event does not necessarily lead to a restructuring of an already-existing conceptual framework. Children will find ways to account for contradictory observations in order to maintain their current beliefs long before they are willing to change their beliefs to fit new evidence. The following examples provide evidence of young children's reluctance to change their naive conceptions in spite of perceptual evidence.

In an exploratory study in which I examined the nature of 6-year-olds' conceptual understanding of the insulating qualities of different materials, young children were unable to account for the surprising result that an ice cube wrapped in sheep's wool hadn't melted after one hour. They were unable to adjust their thinking from their perceptual understanding that wool is hot and keeps things warm to the conceptual idea that wool acts as an insulator and can keep heat out. Hence, experience-based beliefs are firmly established and are not easily changed. The perception of materials as hot and cold conflicts with the scientific conception of insulation, a property of certain materials that reduces energy transfer from one place to another .

Similarly, a study investigating 10-year-olds' understanding of buoyancy (Bickerton & Porath, 1997) indicated that children at this age were unable to explain the phenomenon of why one block of rosewood sank while another block of the same size but made out of cedarwood floated. Confusion arose due to the children's firmly established belief that all wood floats. The students were willing to modify their experiments to accommodate their beliefs long before they were willing to accept the need to change their beliefs to fit the evidence. In spite of formal science instruction, the more obvious perceptual features still tend to dominate children's thinking and govern their reasoning regarding scientific phenomena. Consequently, science educators are faced with an interesting paradoxical task, albeit a very difficult instructional challenge, making *invisible* phenomena (e.g., density) somehow '*visible*' through experimental investigations. Driver (1985) postulates that children gradually learn to wear 'conceptual spectacles' which involves constructing mental models for entities which are not directly perceived such as density, force or particles of matter.

Summary. The perceptual-conceptual distinction is important to the theory of cognitive representations and to the development of children's scientific reasoning. In the area of scientific reasoning it is important to maintain a distinction as the proposition "seeing is believing" in science is not often true. In fact, we have seen examples of how perception can block conceptual change and also how conceptions remain steadfast in spite of perceptual counter-evidence. This complex interactive process between perceptual and conceptual representations reflects the architecture upon which mental models are constructed. Perceptual representations are constrained by the current perceptual input whereas conceptual representations require not only time but considerable effort on the part of the learner to construct complex models.

Although I have given examples of how perception may block conceptual change in a child's understanding of scientific knowledge, it may also be instrumental in effecting conceptual change. Perception may expedite what Piaget (1968) called "reflective abstraction" which enables children to reflect on their own thinking. When conflict occurs between new evidence and a child's set of beliefs, it suggests that the knowledge representation employed is fragmented and consists of a number of restricted aspects that are not connected together in a coherent way (Halford, 1993). Since children's minds are constantly "under construction," Vygotsky (1962) claimed that conceptual change can only take place within the "construction zone," in other words, what a child is developmentally ready to consider. He indicated that developmental factors such as memory, knowledge acquisition and reasoning ability affect a child's capacity to incorporate new knowledge into existing schemas.

Children's minds are constantly in motion trying to make sense of everyday phenomena in their physical world. As constructive thinkers, children generate an understanding of specific concepts within the developmental constraints of their information processing capacity at various stages in their cognitive development. More specifically, the cognitive structures and processing strategies available to children at certain points in their development orchestrate what environmental information they select that is meaningful to them and how they represent and transform what is selected in accordance with their cognitive structures. As Flavell (1992) succinctly suggests, children are in essence "manufacturers of their own development" (p. 998).

For many decades, cognitive developmental research has revolved around the question of what children understand about their physical world (Piaget & Inhelder,1942/1974). However, it is only recently that researchers have shown a genuine interest in defining what it means to understand something and in describing the basic processes entailed in understanding. The following section is concerned with mental models and their role in understanding.

Mental Models and their Role in Understanding

The importance of understanding is clearly evident in educational research in the areas of math and science. Knowing when to apply memorized formulas to solve specific physics problems is not necessarily indicative of conceptual understanding. In fact, when students are asked to explain physical phenomena, they do not typically invoke formal rules from logic or mathematics but construct mental models of a qualitative nature to represent their premises or conceptions. Therefore, mental models are content-specific representations consisting of specific examples rather than logical principles. For instance, in my study investigating gifted young scientists' reasoning about buoyancy (Bickerton & Porath, 1997), one 10-year-old's explanation for why his model boat sank implied an intuitive understanding of density with this response : "It wasn't the right volume for the weight of the boat." Although he had no formal knowledge of the mathematical formula for density (defined as the mass of any substance divided by its volume), this student demonstrated an intuitive understanding of the concept by focusing on the two very important basic principles: (1) the integration of weight and volume and (2) an understanding of proportional reasoning (although in its primitive form).

Interestingly, investigations of high school students' performance on physics problems reveal that misconceptions persist in spite of their successful completion of courses (McCloskey, 1983). Hence, successful performance on scientific tasks should not be considered indicative of a student's conceptual understanding. Recall from Chapter 1 that diSessa (1988) claims that physics students possess "a fragmented collection of loosely connected ideas that constitute a series of independent layers of understandability" (p.55). Therefore, educators should not categorize students as understanding a concept in an all-or-nothing fashion especially on the basis of how an individual performs on experimental tasks. Instead, we should determine what a student understands in that test, how his or her response was generated and how that performance would generalize to other similar tests. Mental models provide us with the theoretical tool and conceptual framework to deal with such questions.

Understanding involves having a mental model or an internal representation that corresponds to a particular concept or situation. For instance, a mental model might be specifically constructed for a problem solving task representing a child's procedural knowledge and/or it might consist of a general schema of domain-specific knowledge induced from experience which serves as a "template" to structure the representation of the problem (Halford,1993). According to Halford (1993), understanding is the ability to represent concepts or situations in a way that is "general, generative and connected to other representations" (p.17). Mental models should have representations that serve as a basis for understanding. In either case, mental models differ from Piaget's notion of psycho-logic in that they contain relatively specific semantic information. An individual draws upon his or her knowledge about a concept or problem to create representations that form the basis of an individual's understanding of that concept or of how to proceed in solving a problem.

From a slightly different perspective, an alternate line of inquiry was pursued by a group of theorists who investigated the development of children's understanding of representational thought. According to this *theory of mind* research, children cannot make much progress towards understanding natural phenomena in their physical and social worlds until they have some understanding of how the mind constructs mental representations of such phenomena. Understanding how children acquire a common sense epistemology of scientific phenomena consists of understanding their construction of a theory of mind, a process that begins in infancy.

Children's Understanding of Representation. Researchers who study the *child's theory of mind* have demonstrated that, by four years of age, children acquire a representational theory of mind, that is, an understanding of their own and other people's minds (Flavell, 1988; Perner,1991; Wellman, 1990). Children might begin with only a partial understanding of representation. For example, Astington (1993) and Flavell (1988) claim that two- or three-year-olds begin their discovery of the mental world by learning that they and other people have internal experiences that are cognitively connected to external objects or events. However, at this point in time, they have no understanding of mental activity. As children mature, they gradually realize that these "cognitive connections" entail inner, "mental representations" that can change over time. Thus, at about four years of age, children acquire an understanding of representation in both its senses, as a mental state (e.g., belief, desire, intent) and a mental activity (e.g., think, know, believe). They come to the realization that beliefs and desires are not just things that exist in the mind but representations produced by the mind that relate to the world in a specific way.

Four-year-olds understand that beliefs can be independent of reality (Gopnik & Astington, 1988; Keenan, Marini & Olson, 1995; Wellman, 1990; Wimmer & Perner, 1983) in the sense that they can be (1) false, (2) vary across people and (3) can change over time. Once children reach this level of understanding, they understand that people represent the world and therefore do not have direct access to reality but construct the world in their mind. Therefore, around the age of four years, Astington (1993) believes that "children come to understand that people's thoughts are representations constructed by the mind, and that perceptions and beliefs represent the way the person takes the world to be, which may not necessarily be the way it is" (p.174).

According to the theory-based approach to cognitive development (Carey, 1985; Chi, 1992; Karmiloff-Smith, 1988; Keil, 1989), the development of a child's theory of mind progresses independently of and concomitantly to the development of his or her theory of the physical world. Similarly, theorists who have adopted an information-processing approach towards cognitive development (Case, 1985, 1992; Marini & Case, 1989, 1994;

Olson, 1989) argue that changes in children's understanding of the mind effects a general change across a variety of domains (e.g., numerative, scientific reasoning, social). In addition, Case (1985) and Olson (1989) propose that children's developing understanding of the mind is based on the developmental increase in their information-processing abilities, such as changes in memory or computational capacity. Both authors believe that, with development, children have an increasing capacity to mentally represent information and thus conclude that this increasing capacity can serve to explain the general development of children's representational abilities across different domains.

Summary of Mental Models and their Role in Understanding

During the 1960s, curriculum planning involved the formulation of behavioral objectives as an index of instructional success. The term *understanding* was avoided on the grounds that it was so hopelessly vague in its connotation that it could never serve as a meaningful learning outcome (e.g., Mager, 1962). Today, *understanding* is no longer considered a nebulous concept but one that can be clearly defined and usefully explicated for the specific purpose of designing instruction that develops student understanding of certain topics. *Understanding* is emphasized in our schools today because it confers a certain cognitive autonomy on the student. Students demonstrate the extent of their understanding by devising their own way of representing what they know and how they act upon this information.

In terms of mental models, children's conceptual understanding of natural phenomena in the physical sciences has been documented across a wide range of topics such as dynamics, gravity, heat, light, matter and density (Carey, 1985; diSessa, 1988; Driver et al., 1985; Kuhn, Schauble & Garcia-Mila, 1992; Reif & Allen, 1992; Smith, Carey & Wiser, 1985). By utilizing mental models as a theoretical tool, these investigations have provided researchers and educators with valuable information regarding children's understanding of scientific thinking in terms of their misconceptions and naive preconceptions about specific concepts.

Summary of Mental Models

The notion that children have mental models about scientific phenomena provides researchers with a theoretical framework to monitor the development of children's conceptual understanding of a specific concept. Within this flexible framework, researchers are able to delineate what it means to understand something from both a structural and conceptual perspective. This new insight into what understanding is has implications for the design of educational approaches having as their goal the development of understanding. It enables cognitive developmentalists to conduct an in-depth inquiry into the nature of children's concept development in terms of both the general and specific features of children's cognition (i.e., domain-general and domain-specific knowledge). Furthermore, the ontogenesis of conceptual change in scientific thinking can be monitored through the developmental changes in a child's mental model of a specific concept before and after some type of environmental mediation (Carey, 1985; Case, 1985, 1992; Chi, 1992).

Conventionally, curriculum planning in science education involved the development of teaching sequences which were hierarchical in nature starting with the basic concepts and building the unit from there. However, research in the areas of both science education and developmental psychology suggests that knowledge of children's ideas is also important in planning specific programs. Halford (1993) claims that it is more useful to identify the mental model that a child has of a particular concept than to simply categorize the child as understanding or not understanding according to a set of arbitrarily defined criteria constructed by educators themselves based on their own predictions and evidence from empirical data. It is important to know what cognitive processes children employ in performing a task and the nature of the knowledge they bring to bear. In support of this view, a number of different theories were developed to elucidate the structural and conceptual nature of children's and adults' mental models of different scientific concepts. Their intention was to introduce a stronger set of assumptions about the specificity of children's cognitive structures in terms of content knowledge and its schemata, the way knowledge is organized. Furthermore, these theories provided different explanations of varying depths of analyses for how conceptual change occurs in an individual's mental model over time.

SECTION 2

Theories Utilizing the Concept of Mental Models to Investigate Children's Understanding of Scientific Phenomena

In the late 1970s and early 1980s, a number of different theories were proposed regarding the nature and development of children's understanding of scientific phenomena. This section will present and compare the following <u>three</u> approaches: (1) neo-nativist theory, (2) learning theory: novice to expert shift and (3) social constructivist theory. All three research inquiries attempt to combine the general and specific aspects of cognitive development by utilizing the concept of mental models. Studies investigating children's scientific knowledge will be included within the discussion of each theory.

The first general theoretical direction that was taken based its study of children's cognition on the rationalist viewpoint (Kant, as cited in Case, 1995). Psychologists who adopted this viewpoint believed that children come equipped at birth with a primitive set of modular structures, each of which were "prewired" with order imposing devices to pay attention to certain features in the environment and to relate these features in particular ways (Carey, 1985). An attempt to elucidate the nature of these innate structures and monitor the changes that take place in these structures over the course of development became one theoretical approach undertaken by a group of researchers. They became known as neo-nativists who drew their impetus directly from Chomsky's work in linguistics and modular theory (Fodor, 1982).

Neo-Nativism

Popularity of the nativist position originated from convincing research evidence that infants and very young children exhibit capacities or abilities that were generally not acknowledged by Piagetian theory. For example, using nonverbal experimental methods, Spelke (1988) and Baillargeon (1992) concluded that infants are able to form mental representations of objects, though the exact age is still under much debate. Furthermore, infants use external representations as well. By the age of two years, children understand that a picture, toy, word or other "object" can stand for a real object or event (Flavell & Flavell,1988). Such inspiring data on infant's cognitive capabilities led Nativists to postulate that such capacities must be innately specified. Children come "prewired" to process domains of knowledge such as language, number and scientific phenomena (e.g., biology or physical matter), each in very different ways.

Neo-nativist theory views the mind as essentially modular (Fodor, 1982; Gardner, 1983). Based on this notion, several investigators suggested that children's cognitive processes are best conceived as a set of neurologically defined "modules" which are defined by Case (1992) as "domains of functioning" (p. 365). Each module operates in a relatively independent fashion and is preprogrammed for executing its own particular function (Carey, 1985; Fodor, 1982; Gardner, 1983). Thus, the "neo-nativist infant" begins life with a primitive set of modular structures that are pre-tuned to pay attention to certain particular features of the environment and contain fundamental elements upon which all information processing depends (Carey & Gelman, 1991; Spelke, 1988). Within each module, the structural foundations are laid upon which the building blocks of cognition are constructed and these early structures play a key role in determining the nature of the conceptual systems or "theories" that children construct (Carey, 1985, 1988). Over the course of development, the reworking of these structures into more sophisticated or elaborate systems is still based on the same general set of principles or beliefs (Carey, 1985, 1988).

For instance, Smith, Carey and Wiser (1985) described children's development of the concept of density in terms of the acquisition and reorganization of their knowledge about physical matter. These authors believed that children's developing understanding of density is dependent upon acquiring a basic understanding of the properties of matter such as weight, size (volume) and substance. In its early stages of development the concept of density is embedded in a global measure for the quantity of matter which is conceptualized in absolute terms, specifically big or small; heavy or light. In this sense, density and weight (i.e., mass) remain undifferentiated. Between the ages of 4 years to 10 years, children's knowledge about physical matter undergoes a conceptual restructuring that results in a differentiation of the basic properties of matter - weight, volume, substance and density. New relations are formed between these distinct properties that induce changes in children's causal explanatory ideas about physical matter. As new knowledge is accommodated and assimilated into a child's existing conceptual system or "theory," a more elaborate conceptual system is developed. Hence, a sequel of the earlier version has been created as an outgrowth of this gradual and constant reorganization.

Humans are essentially theory builders and from the very beginning we construct explanatory structures that help us make sense of our physical world. It is with this notion in mind that a group of researchers proposed an extension to neo-nativism (that conceptualizes the mind as essentially modular) and launched a theory-based knowledge approach to cognitive development.

Cognitive Development as Theory Development

According to this theoretical perspective, children are either born with, or very early construct, *naive theories* about certain very general domains of their experience. Children are knowledge seekers and, therefore, much of cognitive development is self-motivated (Flavell, 1992). In infancy these theories are very simple. For instance, infants adopt a theory that the world contains permanent objects with boundaries and substance (Spelke, 1988, 1991). Over the course of cognitive development, theories become more complex in nature as children acquire more knowledge about the content area in question. In addition, young children may have only a few theories (Carey, 1985,1991) whereas older children may possess a number of theories for various domains. A postulate of Carey's (1985) is that infants begin life innately endowed with two theoretical systems to begin structuring knowledge about the world around them : a naive physics and a naive psychology. She believed that the nature of the "initial state" or starting point of an infant's learning is an important empirical issue for psychologists seeking explanatory theories of learning as well as explanations for developmental changes.

In a similar vein, Wellman and Gelman (1992) proposed that children may possess a "framework" or "foundational" theory in not just two but at least three areas: physics, psychology and biology. For instance, a child's theory of physics, albeit naive when compared to formal scientific theories (e.g., Newtonian mechanics), may have an understanding of the physical properties and behaviour of inanimate objects and their "physical-causal interactions," such as buoyancy. Cognitive development assumed as domain-specific theory development infers that children's mental models may be articulated as informal or intuitive "theories" about the physical world. According to Carey (1985), these theories are encapsulated in "coherent causal-explanatory frameworks" (p.201). Wellman and Gelman (1992) also based this idea on the premise that (a) children acknowledge the core ontological distinctions made in that domain, (b) they use domain-specific causal principles in reasoning about phenomena in the domain and (c) their causal reasoning coheres to form an interconnected theoretical framework. In other words, children's representational thought, described in terms of theories, is not merely a collection of loosely-connected, perceptually-based ideas but contains conceptual representations that are purposely constructed to explain natural phenomena.

Hence, naive theories are not "knowledge fragments" as diSessa (1988) proposed but cohesive ideas that help children make sense of the world. Empirical data from many studies provide evidence that children's mental models as "naive theories" comprise theory-like conceptual structures that are organized within domain-specific explanatory frameworks (Astington, Harris & Olson,1988; Carey,1985; Smith, Carey & Wiser,1985; Wellman & Gelman,1992; Wiser & Carey,1983). Carey believed that developmental psychologists needed to determine the nature of these "naive theories" in terms of representational thought. Moreover, it was important to consider how they differ from other mental model interpretations.

What are naive theories? The term "theory" has been used with varying degrees of breadth and scope by researchers in this "theory theory" approach to cognitive development

(Astington, 1994; Carey, 1985; Wellman, 1992). Generally speaking, there are two major differences in researchers' interpretations of the term. The first is a microscopic (narrow) view inferring that every child's concept is a theory and, therefore, children develop many specific theories about the world. This microscopic viewpoint proposes that children's concepts have theory-like qualities to them and appear to function in some ways like mini-theories (Carey, 1985; Keil, 1986; Wellman, 1990). Like a theory, a concept serves to (1) explain what children experience in order for them to make sense of their world and (2) guide and constrain the type of inferences made about future information.

The second interpretation broaches the term *theory* from a more macroscopic (broader) perspective, referring to very broad domains of reality in a child's world (e.g., a theory of intuitive behaviour or intuitive physics) within which a number of specific concepts or mini-theories are embedded. For example, Carey (1985) claimed that children's concepts in specific domains are part of larger "naive theories." In other words, individual concepts are embedded in an overall "theory-like conceptual structure" about that domain.

Mental models in terms of *naive theories* differ from other types of cognitive representations in that they are explanatory; they can answer "why" questions. Explanation plays a central role in constructing such theory-like concepts. According to Carey (1985), it is the "explanatory mechanisms" which are essentially core structures comprising fundamental beliefs that distinguish these mental models (i.e., naive theories) from other conceptual structures (e.g., sequentially structured script representations of events). These "explanatory mechanisms" are delineated as causal relations among elements and appear to be at the heart of children's conceptual systems. They play a major role in determining the types of theories that are constructed and the explanations given for scientific phenomena.

The word *theory* was used by Carey (1985) as an analogy to the theories of scientists.

Although children's *naive theories* are obviously not as precise and consistent as formal scientific theories, they are similar in that both undergo continual revision and testing. In fact, the process of conceptual change, within this theory-based approach to cognitive development, is interpreted as an on-going revision of children's naive theories.

Conceptual change and the revision of naive theories. Researchers who have adopted a conceptual-change perspective (Carey, 1985; Chi, 1992) believe that the construction and revision of theories constitute the heart of cognitive development. If this is the case, then psychologists will need to know more about how the process of theory revision occurs. During the course of development, children's "naive" theories of different concepts undergo periodic restructuring (Carey, 1985, Keil, 1986). The nature of these restructurings may be relatively minor in the sense that they involve additional structures and/or the merging of local structures into more general ones. On the other hand, a major reorganization of structures may take place at certain stages of development involving a fundamental "theory" change in (a) the nature and relationships among concepts and (b) the type of phenomena used to explain a specific concept (Carey, 1985; Wiser, 1988).

Changes in any conceptual system are presumed to develop in a local rather than general manner. Hence, conceptual change is confined within the module or specific domain to which the theory is applied. Stage-like change is possible within any given domain but unlikely across domains. Since each child's conceptual system is "informationally encapsulated," it appears plausible that it will follow its own trajectory and develop at its own rate (Gardner, 1983; Keil, 1986).

Children's naive theory of physical matter. One of the goals of developmental research is to characterize knowledge acquisition and knowledge reorganization within a specific cognitive domain. The nature and development of children's understanding of physical matter is one science domain that has interested a number of researchers who have adopted this "naive theory" notion of cognitive development (Kohn, 1993; Smith, Carey & Wiser, 1985; Smith, Snir & Grosslight, 1992). They studied the development of children's concepts of *size*, *weight* and *density*. However, the most well known density studies were conducted by Piaget and his colleague Inhelder (1942/1974). In one of their studies, known as the weight-density study, children compared the weights of objects of different sizes and substances. For example, when comparing a cork with a smaller but heavier stone, children were asked, "Which is heavier?" and were then asked to justify their answers. In another study on buoyancy, Piaget (1930/1972) gave children a collection of objects (wood, stones, toy boats) and asked them to predict which objects would float. The objects were then placed in the water and the children were asked to explain their predictions. Piaget's objective was to analyze the relationship between the logic of the child and the causal explanations given for why an object floated.

The results of these early studies indicated that 4- to 6-year-old explanations for why boats float focused on "a moral necessity" or on one object property in isolation. Children give reasons such as " the boat is cleverer than the stone," or " because it's big" (1930/1972, pp.136-137). At this early age, Piaget claimed there was "an overdetermination of factors mixed up with social obligations" (p.138). Explanatory structures for why boats float were embedded in social and psychological domains. Although 5- to 7-year-old explanations were full of contradictions, children begin to differentiate relevant object properties of size, weight and substance: "The pebble is heavier because it's smaller" or "because it's made of stone" (1930/1972, p.141). In the buoyancy task, explanations for floating were based on dynamic reasons. For example, a boat's buoyancy could be explained by the fact that it was moving.

Piaget's underlying assumption here stemmed from children's implicit understanding of the notion of strength (possibly associated with the power of a boat's motor) in the sense that a heavy boat can propel itself through the water. Eight- to 10-year-old explanations depended on the light weight of the boat to make it buoyant but still lacked a full understanding of relative weight, that is, the relationship of the boat's weight to the weight of water. It was not until the age of 11 or 12 years that explanations referred to relative weight and an intuition of density emerged. Children's reasons became less dynamic; in other words the density of an object was seen to have static significance.

From these studies, Piaget and Inhelder (1942/1974) concluded that young children possess a "global" sense of quantity which is conceptualized in absolute terms (e.g., big or small; heavy or large). Children under the age of 6 years were said to assume that weight, volume and quantity of matter (i.e., density) were completely correlated as evidenced by their use of absolute weight to determine an object's buoyancy. These authors believed that such concepts would be gradually differentiated over the course of cognitive development. This notion was later addressed in 1985 by Smith, Carey and Wiser who conducted a series of case studies that were specifically designed to examine the developmental progression in children's understanding of weight, volume and density. The focus of interest was not so much in identifying the "true age" at which each of these concepts emerge in a child's development but about what exactly develops at different ages. The main objective of their studies was to trace the changing conceptual relations between children's understanding of weight, volume and density at different ages.

Whereas Piaget and his colleagues emphasized the influence of domain-general reasoning abilities on a child's conceptual understanding of density, Smith et al (1985) stressed the importance of domain-specific knowledge. For instance, they believed that children's developing understanding of density is dependent upon acquiring understanding of the basic properties of matter such as weight, volume and substance. Furthermore, Smith et al. (1985) preferred to adopt a more continuous and local view of children's developing understanding of density. They believed that the concept of density is embedded in theory-like structures of the child's larger naive theory of physical matter.

In one task, children were asked to decide which of a pair of objects was "made of heavier stuff." Object properties of size, weight and density were pitted against each other. For example, a larger, heavier object of less dense material was matched with an object that was smaller and lighter but of more dense material. Smith and her colleagues found that 3-year-olds solved density problems using absolute weight. Five- to 7-year-olds used both weight and density though there was a lack of differentiation between the two concepts. Children within this age range appeared to have some notion of "heavy for size" which implies that they are taking into consideration the type of substance or matter that constitutes the object. However, this attention towards the object's matter remained integrated within the dominant concept of weight in the sense that it was not totally differentiated from it.

By the age of nine years, children were said to have made the distinction between weight and density. They were less misguided than their younger cohorts by the greater weight of a less dense block when sorting pairs of objects according to their density. For instance, they were able to distinguish between a larger, heavier object of a less dense material and a smaller, lighter object of more dense material. Although young children lacked a fully differentiated concept of density, the results of Smith et al.'s studies reveal that 3- to 7-year-olds do appear to have a good understanding of the concepts of weight and volume. These conclusions corresponded to Piaget and Inhelder's observations that young children first respond to density questions according to the object's weight. It is not until later in their development that attention is focused on an object's substance suggesting that the notion of density is gradually coming into play when making judgments about which object is "made of heavier stuff."

Young children's difficulty in understanding density may be found in Smith et al.'s (1985) phrasing of the question : "Which block is made of heavier stuff?" An emphasis on "heavier" may quite possibly lead children to focus on weight rather than density. Carey (1991) later theorized that weight and density may not be fully differentiated for either children or adults, as the concepts are so interdependent. Density is a complex concept and it is questionable as to whether young children or even adults are capable of understanding this property of substances. However, the concept of density is built upon young children's experience with placing objects in water to see if they float or sink. Since density (the substance of which an object is constituted) is one important factor that determines an object's buoyancy, then it seems plausible that young children may have an implicit understanding of this complex concept. In other words, children's judgments of buoyancy may provide a critical link to their understanding of density.

The most recent inquiry into children's developing understanding of density was conducted by Amy Kohn in 1993. She developed an experimental task to investigate preschoolers' (3-, 4-- & 5-year-olds) and adults'(college students) understanding of density based on their buoyancy predictions of a novel set of blocks. She wanted to evaluate whether an experimental task could actually elicit responses that were primarily based on a density judgment. The blocks were systematically varied along the dimensions of volume (size), weight and density. All the blocks were made of wood and were hollowed out or weighted with lead to achieve various density levels. Two sets of blocks were made specifically for this experimental task. One set was finished with a balsa wood veneer and another set with aluminum sheeting to give a metal appearance. This systematicity supposedly permitted the researcher to assess which object property influenced each individual's judgments. Unlike the previous studies, Kohn required no verbal explanations from the participants. All she required was a buoyancy judgment from her participants who were allowed to handle each block prior to making a judgment.

Kohn criticized the methodology used in past research, specifically that of Piaget an Inhelder (1942/1974) and of Smith et al. (1985). She identified two factors that she considered problematic. First of all, she claimed that young children's scientific reasoning may have been underestimated as a result of methodological problems in experimental task situations and secondly that previous studies had the tendency to place too much emphasis on children's verbal descriptions. These two factors provided Kohn with the impetus to develop a new experimental paradigm for assessing young children's understanding of scientific phenomena.

The systematization of a set of blocks varying in weight, volume and density enabled Kohn to conduct a factorial experiment in which each dimension became an independent variable. Kohn claimed that by systematically varying the above dimensions of a set of objects, she would be able to "*accurately*" identify which factors guided children's buoyancy judgments. I have a concern with this claim. Factors such as weight, density and volume are so interrelated in determining an object's buoyancy that surely it would be difficult to single out the underlying factor upon which a buoyancy judgment was made without an explanation. Considering the young children's ages, it is highly probable that all three factors were taken into account simultaneously since density is a concept embedded in a notion of absolute weight which was reported by the aforementioned researchers as undifferentiated from the mass of an object at this point in a child's development. In other words, it would be difficult to sort out to what extent which factor was relied on the most without clarification or an explanation from each participant. Moreover, in a young child's mind the concepts of size (i.e., large or small) and volume may not be fully differentiated in terms of semantics which could be confounded by a perceptual-conceptual distinction that might interfere with their buoyancy prediction.

On the other hand, Kohn's (1993) idea of assessing children's and adults' intuitive understanding of density through simple buoyancy tasks with a set of unorthodox stimuli was most original. However, the lack of a verbal explanation accompanying an individual's buoyancy prediction somewhat restricts the interpretation of the results. A simple "barebones" response (Griffin, 1992) from each individual might have provided more insight into which object properties (i.e., weight, volume or density) influenced participants' judgments the most. Although the systematicity of the set of stimuli is an innovative technique, I am not truly convinced that rival hypotheses have been completely ruled out. For instance, to what extent does the guessing factor influence an individual's decision? This confounding variable could be problematic when interpreting the results. The results of Kohn's study revealed that 4- and 5-year-olds made systematic errors in their buoyancy judgments which related to what Piaget called the size-weight illusion. For example, 4- and 5-year-olds made erroneous "sink" judgments for large, heavy objects of an intermediate buoyant density (i.e., density of 0.79) and erroneous "float" judgments for light-weight objects at the intermediate nonbuoyant density (i.e., density of 1.26). Interestingly, similar difficulties with this size-weight illusion were observed with the adult participants while 3-year-olds made correct "sinking" judgments regarding the dense light-weight objects. Therefore, the 3-year-olds in this study did not show the patterned weight errors that 4-, 5-

year-olds and adults made. Possible reasons for this were based on Piaget's (1961/1969) suggestion that the size-weight illusion increases with age up to 11 or 12 years and then declines slightly. What is more likely, Kohn reported, was that the 3-year-olds in her study performed inconsistently as they were probably uncertain upon what features to focus.

In summary, Kohn (1993) conducted an interesting experimental study that assessed young children's understanding of density in a very practical hands-on way. Designing a simple buoyancy task which is a part of young children's experiences made the experiment more meaningful and less contrived. The construction of a set of novel blocks systematically varied along the dimensions of weight, volume and density enabled Kohn to control for an individual's background knowledge and experience. She has made an important contribution to our knowledge in children's understanding of density.

Contrary to the Smith et al.(1985) study in which 3-year-olds relied heavily upon the object's weight when answering density questions, Kohn found inconsistency in her 3-year-olds' buoyancy judgments. They did not systematically base their judgments on any particular feature. She attributed this inconsistency to the young child's uncertainty as to what object properties to focus on when making a buoyancy judgment (i.e., size, weight or density). However, 4- and 5-year-olds appeared to have a "common sense" understanding of density, albeit in a very "global" or implicit sense.

In summary, empirical findings from the foregoing density studies suggested that, contrary to Piaget's claims, children, as young as 3 years, may possess an implicit understanding of density, albeit in a global and an undifferentiated fashion. This primitive conception of matter may provide the cognitive underpinnings upon which a formal mathematical understanding of density may be constructed. The studies reviewed have contributed much to furthering educators' understanding of how children's developing conception of matter emerges. To conclude this section, the strengths and limitations of the neo-nativist approach to cognitive development may be summarized as follows:

Strengths

1. Emphasizes the importance of domain-specific knowledge in cognitive development.

2. Provides a conceptual framework in terms of naive theories to describe and explain children's developing mental models in specific areas of learning (e.g., physics).

3. Offers a general description of conceptual change in a child's thinking in terms of periodic minor and major restructurings of knowledge.

4. Addresses the important empirical issue of innateness and concludes that the mind is essentially modular.

5. Proposes that a child begins life with innately endowed theoretical systems: a naive physics, a naive psychology and a naive biology. They serve as basic explanatory systems to make sense of the world.

Limitations

1. Lacks any explicit description of the underlying mechanisms that induce conceptual change. There is no attempt to combine domain-general changes with domain-specific changes.

2. Describes conceptual transformations in terms of differentiations and coalescences of concepts but lacks any fine-grained analysis as to how this occurs.

3. Emphasizes conceptual changes rather than structural changes that occur with age.

At the same time that children's naive theories about scientific phenomena were being investigated, another theoretical direction for viewing children's cognitive development was being studied. A group of theorists working in the tradition of learning theory decided to use the framework of mental models to characterize differences between "novices" and "experts" in content domains such as physics (e.g., motion, force or acceleration), chemistry, medicine and chess. In fact, this group of researchers viewed the novice-to-expert transition as a good model for explaining cognitive changes that take place in the course of children's development (Chi, 1988; Chi & Rees, 1983). The notion that experts analyze problems at a deeper conceptual level than do novices as a result of having more relevant conceptual knowledge led to a second inquiry known as the novice-expert shift.

The Novice-Expert Shift: The Learning Theory

The movement towards the novice-expert shift evolved from a group of information-processing theorists who were interested in the way individuals mentally represent and process information. With its origins rooted in cognitive psychology, a major research effort was launched toward understanding the difference between the problem-solving processes of "novices" and "experts" in various domains of knowledge (Simon & Simon, 1978). Originally, these terms were used to investigate adults' cognitive transition from a novice to expert state in particular content domains such as physics, chemistry, medicine or chess. The term "novice" reflected someone who was new to a specific field of learning and who had not received any formal training in that area. An "expert" was characterized as a person who had acquired specialized knowledge and skills in that area. In the 1980s, Chi and her colleagues thought that an analysis of the differences in performance between novices and experts on various problem-solving tasks would help to elucidate the nature of structural and conceptual changes which take place in adolescents's learning of science (Chi & Rees, 1983; Chi & Ceci, 1987; Chi, Glaser & Rees, 1982; Larkin, 1983). These cited authors conducted a number of studies in the areas of physical science and mathematical problem solving specifically for the purpose of improving science education.

As the name implies, the study of the novice-expert shift investigates the change that occurs from starting as a novice to acquiring expertise in some domain (e.g., chess). Empirical data from the theory-based approach to cognitive development supported the notion that children's scientific knowledge appears to undergo similar changes that parallel the novice-expert shift in adults (Carey, 1985; Larkin, 1983; Wiser & Carey, 1983). For instance, Carey claims that the conceptual reorganization children experience from the ages of 4 to 10 in the domains of biology and physics is just as radical as the conceptual reorganization adults experience when gaining expertise in a specific area.

The theory gathered greater momentum when educational and developmental psychologists adopted a novice-expert shift as a metaphor for characterizing the changes that take place in the course of children's cognitive development (Chi & Ceci, 1987; Chi & Rees, 1983;). Particular attention was directed towards secondary students' understanding of physical concepts such as motion, mechanics, and acceleration. Researchers were particularly interested in the influence of declarative knowledge on procedural strategies and how this influence affected an individual's approach to solving a task. Their first undertaking was to compare novices' conceptual understanding of a specific concept with that of the experts and investigate how conceptual knowledge and procedural knowledge interact. In later research, Bidell and Fischer (1991) were also interested in the way experts activate knowledge by converting it into useful procedures.

Differences in the Mental Models of Novices and Experts

Within the context of this learning framework, three different research inquiries were under investigation, all of which were working towards a common goal of describing how novices and experts differ in the way they mentally represent and reason about scientific concepts. The areas of interest were: (1) novices' misconceptions about scientific phenomena, (2) differences in problem representation and (3) differences in problem-solving strategies. The most common research investigation over the last two decades has focused on students' conceptions, in terms of their personal constructions about physical phenomena (e.g., diSessa, 1988; Driver, Guesne & Tiberghien, 1985; McCloskey, 1983; Reif & Allen, 1992; Watson & Konicek, 1990). These personal constructions were often described in the literature as *misconceptions* or *naive theories* depending upon the class of theory in which they were being studied. Emerging from this rich body of empirical research appeared a group of investigators who became interested in the role of prior knowledge in student and adult performance both in problem-solving tasks and in concept interpretation (Kuhn, Schauble & Garcia-Mila, 1992; Pozo & Carretero, 1992; Reif & Allen, 1992; Ruffman, Perner, Olson & Doherty, 1993). As a result of this, the study of novice-expert differences in a variety of knowledge domains, especially physical sciences, became a popular method of inquiry. By diagnosing novices' current mental models or misconceptions about a given concept (e.g., motion), researchers were able to characterize students' understandings prior to instruction. Such information identifies for teachers the students' existing level of conceptualization regarding the scientific topic under investigation and consequently where instruction should begin.

Chi and her colleagues' research constituted the second area of investigation. Their main interest was in analyzing the novice-expert differences in problem representation.

These researchers believed that the problem-solving process starts with the solver forming a mental representation of the problem in working memory. One technique that was used for studying problem representation was to ask individuals to sort problems into categories. Chi, Feltovich and Glaser (1981) asked novice and expert physicists to group physics problems according to similarity. Novices grouped problems according to the type of object involved : problems about pulleys in one group, problems about inclined planes in another and so on. In contrast, experts grouped problems according to their method of solution: problems solvable by using the conservation of energy principle in one group and problems using Newton's laws of motion in another group. These results indicated that novices represent more superficial aspects of a problem than do experts.

Experts and novices differ not only in the way they represent problems but also in the way they solve them. Examining differences in problem-solving strategies constituted the third method of investigation in the novice-expert research inquiry. Larkin (1983) showed that when solving mechanics problems, novices used a "working-backwards" strategy and had a tendency to engage themselves in a lot of search activity while trying to find a solution. In contrast, the experts were not lost; they used a "working-forward" strategy. Experts tended to start with the givens in the problem and used these to generate more information that was needed to determine the next step and so forth until the goal was achieved. The way experts organized their knowledge of physics enabled them to approach problems in a more structured way than novices. Unfortunately a study on density was not found within the novice-expert research inquiry. As an alternative, the following study was chosen based on its research findings regarding the differences in how novices and experts structured and organized their knowledge in response to problem-solving tasks in the area of Newtonian mechanics.

A Study of Novice and Expert Differences in Newtonian Mechanics

An interesting example of a study conducted within this theoretical framework was one conducted by Pozo and Carretero (1992). The main objective of the study was to examine the effects of conceptual knowledge on reasoning strategies in problem-solving tasks involving mechanics. It incorporated all three methods of investigation discussed above. Pozo and Carretero compared the performance of two groups of university students, one group of physics 'experts' and one group of 'novices' in solving different problems in Newtonian mechanics. While novices in physics, the latter group of students were'experts' in the field of history. In addition, three groups of adolescents from Grades 7, 9 and 11 participated, specifically for the purpose of comparing developmental differences in their performance with the older university students. The tasks were of a manipulative nature requiring participants to first predict the influencing factors and second to demonstrate their ideas or reasons by manipulating the available apparatus. An understanding of concepts such as mass, movement, velocity, acceleration, inertia, force, energy and gravity were required in the problem-solving process.

Pozo and Carretero (1992) analyzed participants' responses in terms of (1) the reasoning strategies they used to solve each task and (2) the concepts or causal ideas they used to interpret this same task. While the former have a general character and can be analyzed independently of the content, the latter relate to a specific knowledge of Newtonian mechanics. An analysis of the responses indicated that the physics experts possessed a clearly different causal knowledge of mechanics than the rest of the students and yet, these 'novice' students (the adolescents' and history students) shared a common pattern of understanding of mechanics. Whereas the 'experts' demonstrated expertise in their understanding of Newtonian mechanics, these 'novices' maintained what McCloskey (1983) called "an impetus theory of motion" that suggests a historical parallelism to medieval and Aristotelian theories of motion. For instance, one of the common misconceptions is that heavy objects fall faster than lighter objects. Although such a notion is fundamentally incorrect in terms of Newtonian mechanics, it tends to be maintained as a result of its environmental confirmation, in other words, due to common experience - seeing is believing.

Interestingly, there were no significant differences in reasoning strategies between ages or groups. However, the central issue determining whether a correct or incorrect solution to the problem was reached depended on the nature of the variables being tested which influenced the type of inferences that were drawn. The main difference in reasoning between novices and experts was that the latter take into consideration a variety of aspects acting upon an object. Experts adopt what is called a "Physical Representation" of the problem based on concepts such as gravitational force, motion and friction. While there was no significant variation across the three adolescent groups in how they used the same reasoning strategy, there was a significant difference between the 16-year-olds and the two younger groups of adolescents in the efficiency of these strategies towards solving the problems.

Quite possibly the increased effectiveness of the strategies was due to a deeper understanding of the basic scientific concepts related to Newtonian mechanics (e.g., mass, weight, velocity, gravitational force and acceleration). In addition, "experts" were undoubtedly helped by the interconnectedness of their knowledge about mechanics which in turn heightened an awareness of the causal relationships between these basic concepts. In other words, all the key concepts of mechanics were connected in an expert's mental model. So the significant difference in efficiency between 16-year-olds and the two younger adolescent groups may have been related more to their causal knowledge than actual differences in reasoning strategies. This hypothesis suggested a direct relationship between causal theories and reasoning strategies in problem-solving tasks.

In summary, the results of Pozo and Carretero's study led to two important conclusions. The first conclusion suggested that age, which is generally related to cognitive development, was not the causal factor that produced differences in conceptual understanding of such notions as force, movement and gravity. In this study, the critical variable appeared to be expertise, which according to Carey (as cited in Pozo & Carretero, 1992) is expertise that is "connected to the acquisition of domain-specific knowledge and its later reorganization" (p.251). Although the history experts were capable of using very elaborate conceptual systems to interpret social phenomena (Pozo & Carretero, 1989), they were unable to construct an equally sophisticated system in providing solutions for scientific problems on mechanics due to a lack of specific knowledge in this area. In fact, results indicated that the university students specializing in history possessed a comprehension of mechanics as limited as the adolescents in the study.

Based on the idea that expertise lies in the accumulation of specialised knowledge, the physics experts seem to differ from the novices in the causal theories they use to interpret the analyzed phenomena. The attainment of expert knowledge entails a learning process which involves acquiring appropriate chunks of knowledge about a specific topic. An example of this conceptual chunking would be learning that *force = mass x acceleration*, that is, learning to represent force by means of integrating the concepts of force, mass and acceleration. Such a novice-expert shift can be characterized as a developmental process requiring time and experience (not necessarily age) that gradually produces efficient knowledge representations as for example, this conceptualization of force.

The study's second conclusion was drawn from an analysis of novice conceptions which, although inaccurate, indicated a consistency in the beliefs that were used to provide explanations for the tasks. Hence, the existence of certain 'implicit causal theories' about the movement of objects appeared to be present. Novice explanations did not merely reflect a set of isolated ideas but appeared to be framed within a general theory or a set of theory-like conceptual structures as hypothesized by Carey (1985). A general consensus among novice-expert researchers is that experts differ from novices primarily in the knowledge that they bring to bear on a task, and also in the interconnectedness of their knowledge, in other terms, how this knowledge is structured. For example, Pozo and Carretero (1992) showed that experts tend to have rich semantic networks in which all the key concepts of mechanics are connected. For example, experts considered the effects of force, gravity and friction on a moving object while novices tended to put things into clusters that did not really make their interrelations clear. For instance, inertia, momentum, speed, velocity and acceleration were clustered together by novices because they all have to do with moving objects.

Generally speaking, most of the novice-expert research has been confined to the study of knowledge acquisition of adolescents and adults within specific content areas; one in particular is the physical sciences. However, educational and developmental psychologists also pointed out that a parallel could be made between the kind of conceptual reorganization children experience in the early stages of development to the conceptual reorganization adults experience when gaining expertise in a new field. For example, Carey (1985) considered that the transition in children's conceptual knowledge of *living things* from the ages of 4 to 10 years represented a novice-expert shift as characterized by the work of Chi, Glaser and Rees (1982). That 4- to 10-year-olds undergo a novice-expert shift in their conceptual understanding of *living things* does not, of course, imply that 10-year-olds or adults for that matter become experts in biology. Patently, they are not.

Acquiring expertise in any specific area is a relative matter; there is room for many novice-expert shifts in the course of mastering content in any particular domain. Therefore, cognitive development may be described as a series of novice-expert shifts that describe the structural and conceptual changes that occur within domains rather than across domains. How knowledge is restructured within each of these novice-expert shifts will now be articulated in terms of developmental changes in children's conceptual representations of specific phenomena.

Developmental Changes in Children's Conceptual Representations

During middle childhood, children's scientific knowledge has been observed to undergo changes similar to the novice-expert shift seen in adults gaining expertise in a new topic area (e.g., chess). For instance, in a study of children's dinosaur knowledge, Chi and Koeske (1983) compared the differences between children's conceptual knowledge of dinosaurs during the early and late stages of middle childhood. The authors observed that the associations between younger children's concepts tended to be weaker and less structured, more idiosyncratic and more perceptual in character than those of older children. Older children's concept representations included a greater number of attributes, more connections between attributes and stronger associations between them. Hence the difference between the younger students' ('novices') knowledge and the older ones' ('experts') was that the older students had greater cohesion in their knowledge of dinosaurs that resulted in much more efficient representations.

As children acquire more experience in any specific domain, they begin to form different relations among the basic concepts which comprise the domain. These new connections may be conceptual, procedural or purely associationistic and lead to the integration of knowledge structures that were previously discrete in the 'novice' or younger child's knowledge network. Once a new and more 'expert' conceptual network has replaced the preceding, 'novice' network, new *strategies* for approaching problems and more efficient processing capabilities emerge (Case, 1985,1992). One strategy that might play an important role in helping to promote an integration of knowledge structures is known as a *conceptual chunking* process. This is when formerly separate items of information are recoded as a single item. *Conceptual chunking* entails the recoding of knowledge representations into conceptual chunks of information which in turn reduces the dimensionality of a representation and thereby decreases the processing load. The dimensionality of a child's representation of a specific concept depends on the number of independent components in its representation (Halford, 1993). As an example, the dimensionality of the concept of density is described as follows.

A dimensional representation of density. The way a concept is represented depends on the number of cognitive operations that are being performed on it. Therefore, the number of dimensions that need to be processed in parallel to understand a specific concept depends on the information that must be represented simultaneously and on the number of independently varying items of information. Consequently, the number of dimensions required to represent a concept is a measure of the structural complexity of that concept. For example, the scientific concept of density is a complex conceptual chunk! In scientific terms, density appears to be a 3-dimensional concept when defined as the mass of any substance divided by its volume: $$\textbf{density} = \frac{\textbf{mass m}}{\textbf{volume v}}$$

Therefore, an 'expert' should be able to represent density in terms of a ternary relationship between the concepts density, mass and volume. However, according to my interpretations, when based on Halford's conceptual-complexity model, that is, the dimensionality of a concept, density becomes a five-dimensional concept. It places demands on children to: (1)

understand units of weight, (2) understand units of volume, (3) integrate the dimensions of weight and volume (as density is defined as mass per unit of volume), (4) understand proportional reasoning if a full understanding of the concept is reached and (5) requires knowledge and understanding of the definitional formula in mathematical terms.

Density is a higher-order property of substances and not a property of objects themselves. Such factors make it likely that this concept cannot be truly understood, if at all, until late in development. However, there are ways by which density can be recoded as a single dimension. For instance, we commonly conceptualize density in its empirical consequence - buoyancy. The buoyancy of an object is dependent upon the object's density and is a property that can be perceived clearly since young children have a great deal of experience placing objects in water and seeing them either float or sink. Kohn (1993) believed that children as young as 3 years do seem to have some expectations or implicit knowledge about the density of certain objects, maybe a sense of intuition. The results of her study supported this notion.

By reducing density to a single dimension (i.e., buoyancy), not only does it reduce the dimensionality of a child's representation of the concept, but it also reduces his/her processing load. However, there are some shortcomings as a result of this procedure. For example, Halford (1993) hypothesized that when we chunk a concept into a single dimension, we use less representational capacity due to the fact that the internal structure of that concept is lost. Consequently, we can now use the capacity freed up by this chunking process to represent other aspects of the concept.

This strategy would be particularly useful in developing a conceptual understanding of density by temporarily "freezing" for a moment our understanding of density as a characteristic of matter and focus on whether an object is buoyant or not. The notion that we represent only a limited number of dimensions in parallel means that we must constantly shift from one level of representation to another. It implies that we create temporary representations in our working memory to provide a workspace for the current cognitive process.

Recoding and conceptual chunking by "experts." The novice-expert shift is argued to be related to the way concepts are encoded (Chi & Glaser, 1988; Chi, Glaser & Rees, 1982). For example, experts construct codes that represent the important structures of phenomena without overloading their processing capacity. Strategies and ability to code concepts in an efficient way are major components of expertise. Expertise entails developing new strategies and adapting old strategies to novel situations. It is probably a more dynamic process than once conceptualized. Moreover, efficient conceptual chunking requires not only that concepts be recoded into fewer dimensions, but that the selection of chunks represent the important aspects of the task. Experts know which are the "powerful" dimensions in a concept. They perceive large meaningful patterns in a domain and represent problems at a deeper level than novices (Chi & Glaser, 1988). Furthermore, the superior memory often recognized in experts is probably due to coding more information into a chunk (Miller, 1956).

Case (1985) proposed that processing efficiency increases with age and plays a key role in promoting cognitive growth. It has long been a contentious issue as to whether processing capacity increases with age or remains constant. In Case's opinion, memory capacity remains constant while developmental changes in processing efficiency occur with maturation. He assumed that the number of chunks or units of information that can be held active in the mind increases from one unit to four units in a recursive manner within each developmental stage of his model. Transition from one major stage to the next involves the reorganization and restructuring of a child's knowledge representation (i.e., the way information is conceptualized). As a result a new qualitative form of representational thought emerges (e.g., a transition from relational to dimensional thinking).

Case (1985, 1993) suggested that increases in processing efficiency effect changes in the type of structure operationally used in the mind and hypothesized developmental shifts in cognitive thought. This process gives the impression that there is a quantitative increase in capacity whereas what has actually changed is the nature of children's representational abilities. In other words, a novice-expert shift has occurred in children's domain-specific knowledge as a result of a more sophisticated encoding of conceptual structures. Hence one of the major underpinnings responsible for producing a novice-expert shift is an increase in children's processing efficiency that enables more complex concepts to be understood (Case, 1993). To conclude this section, the strengths and limitations of the novice-expert research method of inquiry with regard to advancing our understanding of children's development of scientific knowledge can be summarized as follows:

Strengths

1. By comparing the differences in novice belief systems with those of experts this theory attempts to describe the development of children's scientific reasoning and knowledge
2. Offers an explanation of the underlying mechanisms (e.g., conceptual chunking) that may lead to the integration of knowledge structures and increase processing efficiency.
3. Describes the differences between novice and expert approaches to problem-solving tasks in science.
4. Describes the effects of conceptual knowledge on procedural strategies during problem-solving and hypothesizes that there is a complex interactive process between the two types of knowledge.

5. Analyses of "expert" performances help to identify the underlying knowledge required to interpret a scientific concept accurately and efficiently.

6. Demonstrates more interest in external influences on children's cognitive development than the previous theory-based approach to children's learning of science.

Limitations

1. Too much emphasis is placed upon domain-specific knowledge and very little attention is directed towards possible domain-general reasoning schemes or underlying mechanisms that may account for the differences in novice and expert conceptual systems.

2. Novice-expert studies on student's scientific conceptions are task- and domain-specific. Therefore, it is difficult to generalize results to other contexts or situations.

3. This theory relies heavily upon instruction and experience as a means of gaining domain-specific expertise and downplays age and accompanying general systemic constraints as a major causal factor in knowledge acquisition.

While each group of theorists maintains a constructivist epistemology, novice-expert investigators showed greater interest in external influences and their affects on cognitive development than the modular theorists who focused their attention entirely on an individual's internal cognitive processes based on personal experiences with the everyday world. The issue of whether social and cultural processes have preeminence over individual processes, or vice versa, remains a topic of intense debate. The position adopted by theorists in the novice-expert and cognitive-development-as-theory-development inquiries focused on personal construction of meanings and the many naive theories that individuals develop about natural phenomena based on personal interactions with physical events in their everyday lives (Carey,1985; McCloskey, 1983). At the same time as the foregoing research programs were being implemented, another group of investigators decided to take the alternate position and study children's knowledge acquisition within social, cultural and physical contexts. Their intention was to move beyond a psychological, individualistic constructivist approach and adopt a more sociocultural view of children's learning while still maintaining a constructivist epistemology regarding cognitive development. Psychologists who accepted this theory became known as social constructivists.

In a social constructivist framework, psychologists investigated children's understanding of scientific phenomena while working in social contexts. While not denying the importance of autoregulative processes (i.e., personal constructions created by the individual), social constructivists place more emphasis on children's physical and social experiences in characterizing the process of cognitive development. This group of researchers view children's development of scientific knowledge in terms of social construction. In the next section children's social construction of knowledge through interactions with peers and knowledgeable others is considered.

Social Constructivists and Sociocultural Theory

In contrast to a purely cognitive analysis of children's mental models of scientific reasoning and conceptual knowledge about specific scientific phenomena (a major focus of the two previous methods of inquiry), sociocultural theorists tend to assume from the outset that cognitive processes are subsumed by social and cultural processes. They believe that knowledge acquisition depends on a culture's symbol systems (e.g., language, numbers) together with the conceptual frameworks and conventions underlying their use. With their roots in sociocultural theory, social constructivists recognize that learning involves being introduced to a symbolic world. Such cultural experiences play an increasing role with age in shaping children's cognitive development. Consequently, whereas cognitive psychologists analyze thought in terms of conceptual processes located within the individual, social constructivists take the 'individual-in-social-action' as their unit of analysis (Rogoff, 1990; Vygotsky, 1978). From this latter perspective, the primary issue is that of explaining how participation in social interactions and culturally organized activities influences children's cognitive development.

Socioculturalists addressed this issue in a variety of different ways. For example, Vygotsky (1978) emphasized the importance of social interaction with more knowledgeable others. For instance, in the school setting, children learn in specific contexts through a process of guided participation in which the teacher provides various kinds of help tailored to the children's current level of knowledge and skill within what Vygotsky describes as the "zone of proximal development." Vygotsky defined the zone as the difference between a child's independent level of understanding and a child's potential level of accomplishment with a more knowledgeable person, usually the teacher. This zone, often called the "construction zone," encompasses what a child is developmentally ready to consider. Based on this perspective, scientific knowledge and understandings are constructed when individuals socially engage in talk and activity about shared problems or tasks.

Current researchers use a generative teaching model (Bloom, 1995; Woodruff & Meyer, 1995) to investigate children's social construction of scientific knowledge. While working in small groups, students actively generate ideas and explanations regarding different topics (e.g., light and shadow, density). They work as "collaborative cohorts" in a consensus-building process; their main goal is to reach a group explanation for and a mutual understanding of the topic under investigation. Inquiry discourse and consensus-building within small groups of students are socially mediated processes and are conjectured by

Woodruff and Meyer (1995) as critical components of knowledge growth. The inclusion of a consensus-building component in this generative teaching model enables researchers to investigate the nature of students' ideas, arguments or explanations while engaged in small-group inquiry activities. The main focus of Woodruff and Meyer's research was to investigate the "socio-cognitive discourse of students engaged in knowledge-building" (p.2).

Although explanations are situation-specific and consequently based on ad hoc reasoning, students converge on an idea and provide a mutual explanation. In group activities like these, a shared mutual understanding is established by participating in a communicative discourse involving explanation, justification and a negotiation of meaning. Therefore, from a social constructivist viewpoint, making meaning is a dialogic process involving persons-in-conversation. Interestingly, some researchers argued that the commonalities found in children's informal reasoning is partly due to shared ideas and sense-making conversations with peers (Arlin, 1990; Carey, 1985; Driver et al., 1994). The next section will describe how social constructivists interpreted children's mental models of scientific phenomena.

Mental Models as Conceptual Frameworks

Examining children's discourse provides opportunities for educational researchers to delineate the social and individual dynamics of children's thinking and how this interchange of ideas contributes to the construction of meaningful understandings. In order to do this, Driver and Erickson (1983) created a construct specifically for the purpose of capturing students' knowledge-in-action, that is, while they are engaged in carefully constructed problem-solving tasks. The term "conceptual framework" was developed to articulate the nature and organization of conceptual structures which represent the way students conceptualize and respond to specific events and phenomena. In other words, "*conceptual* *frameworks"* are another variation of the use of mental models in research methods of inquiry. Mental models interpreted as "*conceptual frameworks*" are used to *frame* students' scientific reasoning in situational contexts.

While there is a general consensus of opinion among theorists (e.g., Carey, 1985; Driver, 1985; Driver, Asoko, Leach, Mortimer & Scott, 1994;Woodruff & Meyer, 1995) that students construct beliefs about scientific phenomena, the techniques used and the manner in which these mental models are articulated vary considerably from study to study. The reason for this variation is that researchers have adopted different units of analysis to define student conceptual frameworks so it is difficult to compare the findings across studies as a result of this. Some investigators used the framework to delineate individual beliefs while others used it as a group composite of ideas which were mutually shared by students working collaboratively. The latter application of student conceptual frameworks was utilized by Woodruff and Meyer in their studies of student-generated explanations of light and shadow phenomena (1994) and density (1995).

Notwithstanding the diversity in the use and interpretation of documenting student frameworks, this technique of framing children's knowledge-in-action is a potentially powerful method of eliciting student predictions and interpretations in problem-solving activities. A description of students' mental models of scientific reasoning, while interacting with the natural world as observers, or manipulating materials as experimenters and problem solvers, enables researchers to analyze the type of conceptual structures students use in generating responses. In studies of this kind, students are presented with a problem, asked to make a prediction of the outcome and to provide reasons for their predictions.

In the late 1970s and early 1980s, clinical interviews were a popular methodology used to explore children's "conceptual frameworks" in different scientific phenomena including heat and temperature (Erickson, 1979; Erickson & Tibergien, 1985), light (Guesne, 1976) and the particulate nature of matter (Novick & Nussbaum, 1978). According to these cited researchers, commonalities found in children's conceptual understanding of the physical world were partly due to common perceptual experiences and a consequence of talking about particular phenomena with others in which shared meanings are established. Driver and her colleagues (1994) argued, therefore, that "informal ideas are not simply personal views of the world, but reflect a shared view represented by a shared language" (p.8). In other words, students socially construct a "common sense" view for describing and explaining the world. Taken from this viewpoint, the process of learning science is primarily one of social construction. In other words, personal experience, language and socialization are critical factors in the learning of science in schools. Driver's (1985, 1994) work on children's ideas in science has addressed the ways in which school-aged children's informal knowledge is drawn upon and interacts with science instruction.

Common sense knowledge versus scientific knowledge. Driver et al. (1994) and Kohn (1993) believed that children possess a "common sense" view of scientific phenomena and draw upon a range of knowledge schemes to interpret these phenomena. According to these authors, these knowledge schemes are strongly supported by personal experience and socialization. Moreover, Driver (1994) claimed that "children's everyday ontological frameworks evolve with experience and language use within a culture" (p.8). This premise corresponds with what naive and novice-expert theorists describe as radical restructuring of children's domain-specific conceptions (Carey, 1985; Vosnidou & Brewer, 1992).

Common sense ways of explaining scientific concepts differ from the formal knowledge of the scientific community. Children develop their own ideas about physical phenomena based on their everyday experiences and the conceptual schemes or mental models they create to interpret or give meaning to such experiences. Young children begin with a 'common sense' epistemology, acquiring knowledge directly from sensory or perceptual experiences (Carey & Smith, 1993). Some researchers claimed that such informal knowledge acquired ad hoc is internalized unproblematically and appears in the form of a collection of beliefs rather than in the form of a theory (Chandler,1987; Kuhn,1988). Carey and Smith (1993) suggested that common sense reasoning is pragmatic, that is, ideas are formed on an ad hoc basis and judged in terms of their usefulness for specific purposes or in specific situations. These ideas tend to be implicit or without explicit rules.

Scientific reasoning, by contrast, is characterized by the explicit theories in which rules, formulas and specialised knowledge are applied. Formal scientific knowledge is more global than common sense knowledge in its endeavor to construct a general and coherent picture of the world. Hence, the learning of science involves initiating students into a different way of thinking about and explaining the natural world. If everyday representations of specific phenomena are very different from scientific representations with regard to their epistemological and ontological structure, then learning science may prove difficult for some students.

Analyses of students' discourse regarding their conceptual understandings of different scientific phenomena suggest that personal experiences and formal scientific conventions are incorporated into and processed by children's interpretive frameworks (i.e., mental models). A study conducted by Bloom (1995) exploring children's discourse and understanding of buoyancy confirmed this hypothesis. While engaged in sense-making conversations with their peers, students commonly drew upon examples from personal experiences entrenched in everyday situations and from instructional science learning. They utilized these examples to support their claims and counter arguments.

<u>The nature of scientific knowledge.</u> The symbolic world of scientific knowledge entails a unique vocabulary of language consisting of socially-negotiated, man-made constructs. Scientific constructs (e.g., atoms, buoyancy, density) have been invented to interpret and explain natural phenomena and are characterized as the conventions of science. Such scientific knowledge of this formal nature is unlikely to be learned through a process of discovery based on children's own empirical inquiry. Instead, it is socially constructed by way of a process of enculturation within a scientific community (e.g., schooling).

Case (1995) described education, from a sociohistoric perspective, as one of "initiation into authentic social praxis" (p.16); in other words, the process of learning scientific concepts is presumed to be one of acculturation : initiation into the symbolic world of scientific knowledge. Instead of involving children in a process of individual sense-making about different scientific phenomena, the role of the science educator is to create a science community in which students (1) share their understandings, (2) engage in dialogue on the nature of these experiences and (3) learn the symbolic representations (i.e., definitional formulas) of scientific concepts and models of conventional science. The challenge lies in helping students "appropriate" these symbolic or cultural tools for themselves and know how and when to apply them in their own scientific investigations.

<u>Learning science as both an individual and social process.</u> While knowledge construction is taking place on a social level, an internal process is simultaneously at work personally constructing and making sense of new information acquired from the social milieu. In other words, an individual is constantly reworking his or her conceptual frameworks within specific domains of knowledge. Often during student-teacher interactions, attempts are made to "scaffold" students' reasoning to facilitate the internalization process of an individual's personal sense making (Bruner, 1986).

Interestingly, both Bereiter (1994) and Cobb (1994) question the need for distinguishing between individual and social constructivism except for the pragmatic research difficulties of investigating both approaches to learning at once. They proposed that a basic tenet of any theoretical inquiry into the nature and development of children's cognition is that "*learning is a process of both self-organisation and a process of enculturation that occurs while practicing in cultural practices, frequently while interacting with others.*" (p. 18). The central issue, therefore, is not to debate whether one has primacy over the other in the learning process but to explore ways of coordinating constructivist and sociocultural perspectives by gaining more insight into the nature of this reciprocal interactive process.

The next section will examine the nature of the internalization process from a social constructivist's viewpoint and articulate possible mechanisms that induce conceptual change. Internalization, by definition, is an individual constructive process. However, social constructivists believe that it is the integration of the "internal" and the "external" (Vygotsky, 1986). From this viewpoint, internalization implies the process by which children transform and make sense of knowledge constructed externally through social interactions.

A Social Constructivist's Perspective on Internalization

The general belief of social constructivist theory is that one internalizes what takes place externally in social relations mediated by a more knowledgeable person. However, one of the modern-day interpreters of Vygotsky is Roy D. Pea (1993) who questioned the meaning of this "internalization" and claimed that there must be a more "generative" process involved. According to Halford (1993) one of the essential properties of understanding is *generativity*. Halford stated that representations or mental models must be generative so that predictions or inferences can be made from them that go "beyond the information given"

(Bruner, as cited in Halford, 1993, p.8). In other words, mental models assist learning because once a representation of a specific concept has been constructed it can be used to predict and formulate new information which becomes instrumental in further understanding.

Social constructivists believe that meaningful interaction with others through discussion and experimentation during science investigations is one process by which children's implicit knowledge can be promoted to a higher conscious level of understanding. Pea (1993) claimed that "persons collaboratively construct the common ground of beliefs, meanings and understandings that they share in activity as well as specify their differences," (pp. 268-269). He proposed two underlying generative mechanisms in the conversational learning process that bring about conceptual change: (1) meaning negotiation and (2) appropriation.

Meaning negotiation is the fundamental mechanism of conversational interaction involving exposure to (1) diverse interpretations regarding a specific concept, (2) restatements or reformulations of one's beliefs upon requests for clarification, and (3) the process of confirming and repairing shared meanings that lead to a convergent understanding among the persons-in-conversation. The second mechanism, *appropriation*, originates from the work of Vygotsky who characterized learning in terms of a sociohistorical process of the "appropriation of cultural tools." This notion is based on the premise that learning involves being introduced to a symbolic world through active participation with others in culturally organized activities in which the "tools," which, in this case, refer to the conventions of science (e.g., scientific constructs and theoretical systems) play a key role. What is meant by the term "appropriation" is : (a) one's interpretation of the knowledge exchange with others; in other words, extracting meaning from others about the scientific way-of-knowing and (b) incorporating and applying these newly acquired cultural practices into one's own conceptual frameworks. Since conceptual change is a gradual process, meaning negotiation and appropriation need to take place over many activities and conversational sessions.

Studies conducted within a social constructivist framework focus on the way a learner's common sense knowledge about the physical world interacts with classroom instruction on the conventions of science (Driver, Guesne & Tiberghien, 1985; Pea, 1993; Watson & Konicek, 1990). Researchers were interested in how students "appropriate," that is, internalize the symbolic representations of science into their existing conceptual frameworks regarding different phenomena. Some researchers have explored the possibility of children possessing multiple representations or knowledge schemes within their conceptual frameworks, each appropriate to specific contexts. In other words, children may develop a *conceptual profile* of different ways of thinking about specific phenomena. Based on this assumption, children's conceptual frameworks may be characterized by parallel constructions of different perspectives of a scientific concept (e.g., physical matter) that can be drawn upon depending upon the type of context in which it is being applied.

For example, considering matter from a quantum perspective (i.e., the weight of a substance), is different from an atomistic view that focuses on the particulate nature of a substance. On the other hand, a common sense understanding of matter usually suffices when dealing with the different properties and behaviour of solid matter in everyday situations. Hence, the internalization process may be characterized as children developing different ways of thinking, that is, having a *conceptual profile* for different scientific concepts.

Summary of a Social Constructivist Perspective

One of the core postulates of social constructivism is that cognitive growth is far more responsive to external influence than what was believed by the foregoing theories.

Furthermore, the development of children's scientific knowledge is particularly dependent upon the type of social interaction proposed by Vygotsky (1978). In the context of school science, Vygotsky believed that the main source of cognitive change lies within the interactive processes by which new scientific meanings are negotiated among children or between children and their teachers. Teachers support students in guided participation, structuring tasks and "scaffolding " their reasoning as they gradually progress through the *zone of proximal development* **(ZPD).** In summary, social constructivists believe that the learning of science is a knowledge-construction process involving both individual and social activity (Driver, Asoko, Leach, Mortimer & Scott, 1994 ; Pea, 1993; Woodruff & Meyer, 1995). However, they do not propose two separate entities - the child and the environment, but consider the *child-in-social-context* as a single irreducible unit of study. The impetus for conducting studies within this tradition stemmed from the need to emphasize the importance of sociocultural practices in the learner's milieu.

From a substantive viewpoint, there was an interest in exploring the effects of different types of social interactions or culturally organized activities on a child's development of scientific knowledge. More specifically, educational researchers were interested in exploring the social dynamics of education, examining the role of the science educator in mediating scientific knowledge for learners and the process by which new meanings are negotiated with other children, or between children and their teachers. As a result, case studies of conversational analyses of students' scientific discourse have become a popular research strategy (e.g., Bloom, 1995; Driver, Asoko, Leach, Mortimer & Scott, 1994; MacDonald & Kass, 1995; Woodruff & Meyer, 1994, 1995) .

Accompanying this field of inquiry has been the invention of new research methods that attempt to move beyond assessing children's understanding of specific scientific concepts based on their task performance in controlled and contrived experimental settings. Social constructivists agreed to move into more naturalistic settings to conduct their research investigations. As a result of this new research trend, studies were designed to address more authentic, everyday problems within the social milieu of classrooms. The use of ethnographic techniques for describing educational practices as, for example, recording student inquiry discourse during hands-on problem-solving tasks, has now become a prevalent way of documenting students' conceptual frameworks (i.e., mental models). Notwithstanding the many strengths of social constructivism's contribution towards advancing our understanding of how social and cultural activities impacts on children's personal constructions of scientific phenomena, some limitations also need to be considered.

Strengths

1. Studies provide a closer analysis of the dialectical interaction between the internal and external constructive processes simultaneously at work in the development of children's mental models of scientific concepts.
2. The development of an integrative unit of analysis, the *child-in-social context*, exemplifies the basic belief that the social and cognitive aspects of learning are inextricably connected.
3. Researchers have attempted to explain how socially mediated processes, for example, student inquiry discourse, influence children's cognitive growth. Particular attention has been focused on the ways in which students' informal knowledge is drawn upon and interacts with science instruction.
4. Constructs such as the *zone of proximal development* (ZPD) and *appropriation* provide a framework for explaining how the internalization of more complex structures take place. Characterized as a socially mediated process, the ZPD is identified as the central locus for constructive activity and for conceptual change.

5. Cognitive change is characterized and explained through the interactive process between the social world and the changing individual.

6. From a methodological point of view, conceptual change can be observed and documented within the ZPD functional system in terms of both cognitive and interpersonal mechanisms that play a critical role in inducing change. Studies attempt to observe the interactive process of teaching and learning.

7. The identification of meaning negotiation and appropriation as underlying mechanisms of conceptual change during inquiry conversations enables educators to conduct an on-going evaluation of the effectiveness of their instructional methods.

8. The invention of new research methods encouraged researchers to conduct studies in more naturalistic settings, particularly the classroom, specifically for the purpose of gathering data on students' *knowledge-in-action.* Assessment techniques are framed within a situational context and elicit students' conceptual understanding while actively engaged in problem-solving tasks.

9. This theoretical approach has many practical implications for the teaching of science since its main area of interest is in examining the effects of different instructional practices on children's cognitive development.

Limitations

1. There is a tendency to focus on the "snap-shot" model of assessing children's conceptual understanding of specific scientific phenomena rather than a continuous monitoring model. Very few studies have used a microgenetic approach that observes students' learning over time.

2. Although Vygotsky's concept of the zone of proximal development provides a framework that documents the sequence of instruction for accomplishing a specific learning task, it offers

limited scope for documenting the long-term process of cognitive development. The ZPD approach to the development of children's scientific learning provides a microscopic (narrow) view that is essentially task-specific. There is no reference of how learning within the ZPD relates to a child's overall cognitive development.

3. Internal constructive processes tend to be reduced to or constrained within social representations of scientific phenomena. The assumption that an individual's conceptual system will "approximate" the system of interactions constructed in the ZPD only lightly brushes the surface of what actually takes place within the individual's mind.

4. A descriptive analysis of how external information is (re)organized and structured into personal conceptual schemes is not a major focus in this research inquiry. Hence, this approach fails to strike a balance between the individual and social processes of learning.

5. Cognitive development is viewed as too atomistic in the sense that learning is domain-, task-, and context-specific. Therefore, the problem of transfer, that is, children's ability to apply what they have learned to new situations has not been addressed. Although the responsibility for learning a task within a ZPD is shared by both the teacher and the child until the child is able to perform the task independently, it does not necessarily follow that this new knowledge will be generalized to other similar situations.

6. Possible general systemic constraints on an individual's learning appear to be rejected or generally overlooked by this theory. To some extent, constraints on development are accounted for within the student-teacher mediation process itself. They are linked to the difficulties and limitations in the process of appropriation of new knowledge. There is no guarantee that a child's representation of a learning task will simply mirror that of the teachers. Each step within the **ZPD** is an interactive process with a variety of possible outcomes which are determined by a child's own appropriation or understanding of the

instructional activity. From this perspective, development is constrained by children's personal sense-making constructions of the interchange of ideas between the teacher and themselves.

The three theories that have been presented so far in this chapter share some common fundamental beliefs regarding the nature and development of children's scientific knowledge. To a considerable degree, these commonalities are a result of a dialectical shift in perspective in the field of cognitive development regarding the issue of whether cognitive development proceeds in a general or specific fashion. In the early 1980s, these developmental theories suggested that the generality in children's cognition was localized within domains rather than across domains as Piaget had presumed. In contrast to Piaget's domain-general theory in which development was assumed to proceed through a fixed sequence of general, universal stages, these contemporary theories adopted a local view of development that emphasized the importance of domain-specific knowledge (e.g., Carey, 1985; Chi & Rees, 1983; Case, 1985, 1992).

To conclude this section of the chapter, Table 2.1 summarizes the general postulates of each theory regarding how the mind is conceptualized, how mental models are interpreted, and how the processes of learning, conceptual change and overall development are delineated.

TABLE 2.1
Summary of the Three Theories

Theory	Proponents	Mind	Mental Model	Learning	Development	Process of Conceptual Change	Instructional Implications
Cognitive Development as Theory Development	Carey, Smith, Astington, Spelke Wellman & Gelman	A primitive set of modular structures innately specified for each domain of knowledge	Naive theories constructed to explain physical phenomena Theory-like conceptual structures in a causal-explanatory framework.	Child-as-theory builder Formation of a conceptual system built upon a set of beliefs	Minor and major restructuring of theories Developing notions of causal explanations for physical phenomena leading to theory change	Changes in basic causal explanatory ideas that induce theory change	Engage students in genuine scientific inquiry: exploring, developing, evaluating, own ideas. Emphasize theory-building
Learning Framework: Novice to Expert Shift	Chi, Glaser & Rees Larkin, Reif & Allen Pozo & Carretero	Computer-like system Information is processed and transformed into a mental representation	A conceptual system of knowledge networks: Problem Representations & Problem-solving strategies	Gaining domain-specific expertise Accumulation of specialised knowledge	Novice-Expert Shift Reorganisation & Restructuring of domain-specific knowledge	Conceptual recoding of knowledge reduces processing loads & leads to new strategies for problem-solving	Diagnose conceptual understanding prior to instruction. Analyze expert strategy. Train students to recognize contradictions between own & scientific explanatio
Social Constructivism	Vygotsky, Pea, Watson & Konicek Arlin, Woodruff & Meyer	Capable of using language to communicate with others to learn scientific conventions	Conceptual frameworks of children's knowledge-in-action while engaged in problem-solving tasks	Child as apprentice in a social & cultural process. Consensus-building of knowledge within a community of learners	Dialectical interaction between the changing individual & the social world. Involves the internalization of social interactions	through meaning negotiations with others during scientific inquiry, an individual appropriates the scientific tools independently by incorporating new skills into conceptual framework.	Create a community of learners Engage in small group discourse scientific inquiries Role of teacher is to introduce scientific conventions & provide support & guidance.

An Alternative Theoretical Approach to Cognitive Development

In this section, a new theoretical perspective will be presented that maintains the strengths of the theories reviewed and addresses their limitations. A group of researcher-theorists known as neo-Piagetians have attempted to retain a general-systems perspective that reflects many of Piaget's core epistemological assumptions while at the same time utilize a modular framework that delineates the development of children's concepts and skills in specific domains of knowledge (Case, 1985,1993; Fischer, 1980; Halford,1982). Researchers in the neo-Piagetian tradition have committed themselves to the notion that children's cognitive development includes processes that are general and stage-like, a core postulate of the classic Piagetian theory, as well as those that are domain-, task-, and context-specific which is characteristic of the domain-specific theories (e.g., novice-expert and the neo-nativist).

Neo-Piagetian theory differs from Piaget's with respect to: (1) the nature and development of children's operative structures within stages (i.e., logical vs. conceptual structures); (2) the transitional processes that induce qualitative changes in children's thinking from one stage to the next and (3) the degree to which social experience, particularly schooling, influences children's progress from one stage to the next. Since educators questioned the utility of Piaget's notion of a general system of logical operations as a means of explaining how children acquire their knowledge of the world, neo-Piagetians introduced a set of conceptual structures to describe the specificity of children's learning and its environmental dependence. In so doing, this new theory has educational relevance to the teaching of science by combining a concern for children's general development with a concern for the teaching of specific subject matter (e.g., buoyancy).

In the following final section of this chapter, a detailed description of Case's (1985,

1992) neo-Piagetian model will be presented in which Case proposed a new construct, namely the central conceptual structure, to replace Piaget's notion of logical structures. Central conceptual structures differ from Piaget's in that they contain content that is semantic, not syntactic, and underlie children's thought in fairly broad domains of application, such as social, spatial, scientific reasoning or quantitative. A discussion of how this new construct is believed to bridge the gap between the general and specific perspectives on cognitive development will also be included. I will conclude by illustrating how Case's cognitive-developmental model can be used to chart the development of children's understanding of buoyancy.

SECTION 3

Neo-Piagetian Theory

A neo-Piagetian Perspective on Cognitive Development

One of the intentions of neo-Piagetian theory was to preserve the strengths of the classical tradition while eliminating some of its weaknesses. Since one of the strengths of Piaget's theory was to explain the universal features of cognitive development, most neo-Piagetian theorists retained the following traditional postulates regarding the general features of children's cognitive development.

1. Children construct knowledge from their actions on the environment. Therefore, cognitive structures or mental models that entail conceptual understanding must be actively constructed and controlled by the child.

2. Children's cognitive operations proceed through a universal sequence of developmental stages from sensorimotor to representational structures of increasing

complexity.

3. Stage-like characteristic understandings that transcend any particular task can be identified. Children's conceptual understanding has a distinctive organization or structure at each level.

4. Children experience qualitative changes in their understandings of the world as a result of the structural reworking of existing cognitive structures. The processes of maturation, social experience and motivation play a facilitating role in inducing change.

5. A new form of qualitative thought involved the differentiation and coordination of existing structures (Case, 1992).

Most modern theories of cognitive development are seen to challenge the classic structural view that offered a very general explanation of the developmental cognitive processes that take place within stages and during stage transition. Modern theorists felt that Piaget's notion of a general operative structure had a number of shortcomings regarding the more specific aspects of children's cognitive structures. During the 1980s, a group of researchers, known as neo-Piagetians, decided to revise the general structural postulates of Piaget's theory by introducing a stronger set of assumptions about the specificity of children's cognitive structures and their environmental dependence. The neo-Piagetian theorists agreed to (1) *preserve* the classical theory's broad explanatory power, (2) *develop* a set of structural transformation processes to explain changes within stages and stage transition, (3) *alter* those aspects that were difficult to operationalize (e.g., the notion of system-wide logical structures) and (4) *place greater emphasis* on the influence of social and maturational factors on children's development (Case, 1985, 1992; Fischer, 1980; Halford, 1988; Pascual-Leone, 1970).

Since the classical theory lacked a detailed account of stage transition and transformational processes within stages, neo-Piagetian theorists developed a form of information-processing analysis that would be sufficiently fine-grained to articulate the nature of children's cognitive growth within stages and from one stage to the next (Case, 1985,1992; Fischer, 1980; Halford, 1993; Pascual-Leone, 1988). Neo-Piagetian theory hypothesized that development within each of the major stages "recycles" in a recursive fashion in the sense that the same pattern of structural changes in children's conceptual understanding is repeated. This notion did exist within the classical Piagetian system by the name of "vertical decalage" but was relatively undeveloped. Although Piaget acknowledged that social and maturational factors play an important role in influencing children's cognitive development, by far the most important role was assigned to rational structures and processes based on "logico-mathematical" experience (Piaget, 1964, 1970).

Subsequent theorists had difficulties in defining such logical structures in operational terms and, in fact, the existence of such structures was never demonstrated to the satisfaction of developmental psychologists nor was their relevance to educational practices ever determined (Carey, 1985; Case, 1985, 1992; Chi & Glaser, 1988; Fischer, 1980; Halford, 1988). For example, these cited researchers found a lack of correspondence between the form in which Piaget's structures were articulated (i.e., symbolic logic) and the form in which they were represented in children's minds. Another problem was the difficulty of accounting for cognition that was *not* logical or mathematical, when the underlying theory maintained that logico-mathematical structures were paramount. Furthermore, Piaget spoke of the transformational processes of these logical structures as if they operated on a child's entire psychological system (i.e., the "structure of the whole"). Today's current thinking no longer views cognitive development as progressing through a single set of "structures of the whole," but as progressing along many fronts at once.

Neo-Piagetian theory takes the view that changes in children's cognitive structures and processes take place at both a local and general level. For instance, Case (1985) and Pascual-Leone (1988) have proposed a distinction between general processes which *constrain* and/or *potentiate* development and more specific processes that operate within these general constraints and potentials. Contradictory to Piaget, neo-Piagetians suggested that developmental restructuring is not system-wide in nature but more local (Case, 1985; Fischer, 1980; Flavell, 1988; Halford, 1988). Consequently, a much greater emphasis was placed upon "domain-specific" experience with regard to the development of children's cognitive structures. Instead of interpreting cognitive growth in terms of rational thinking and logical models, neo-Piagetian theory interpreted children's mental models as content-specific representations that illustrated children's conceptual understanding of specific concepts.

According to the neo-Piagetian view, the development of children's skills and concepts takes place in quite a local manner in terms of content-specific knowledge and the type of social experiences. Therefore, the type of cognitive structures to be delineated are not strictly logical or syntactic but instead are conceptual and semantic. Hence, such structures embrace a wide range of knowledge that is specific to particular content domains, an interest of module-specific theorists (e.g., Carey, 1985, 1991; Spelke, 1988) and of learning theorists interested in domain-specific knowledge networks (e.g., Chi, 1983; Chi & Glaser, 1988). In this sense children's cognitive structures take on a multidimensional nature, in terms of the existence of many possible different kinds of conceptual structures that are central to children's thinking about a given domain (e.g., numerical, social, or spatial). This contrasts with Piaget's unidimensional interpretation of children's cognitive structures in terms of their gradual development towards the ultimate goal of formal operational logic.

Like the classical tradition, neo-Piagetian theory believes that cognitive change is dependent on both biological and sociocultural factors. As previously mentioned, the main source of developmental change in children's thinking in classical Piagetian theory was the qualitative shift in core logical operations or the "structure of the whole" (Piaget, 1970). However, unlike the classical tradition, neo-Piagetians perceive developmental changes in children's thinking, as originating from two general sources. The first is a *local change* which involves changes in conceptual knowledge relating to a specific concept or task as a result of motivational and/or school experience. The second is a *general change* due to maturational changes which impose system-wide biological constraints on children's capacity to process information at various points in their development.

Following the lead of Pascual-Leone (1969), most neo-Piagetian theorists agreed that children's attentional capacity or *working memory* is the explanatory construct for general developmental constraints on children's cognition (Case, 1985;1993; Halford, 1993). From a neo-Piagetian viewpoint, the construct of *working memory* refers to the *workspace of thinking*, an active cognitive process which is operationally distinct from but related to short-term memory capacity. As the name implies, working memory involves a system that is responsible for both processing and storing information. Keenan, Marini and Olson (1995) defined working memory as a child's "computational powers," the ability to "hold in mind the product of some mental operation while further operations are performed on that product" (p.5). Keenan et al. (1995) interpreted this construct within the context of children's representational abilities, specifically the notion of "false beliefs."

Two studies were conducted to test the hypothesis that children's performance on a memory span task would predict their performance on a set of false belief tasks. Keenan et al. (1995) argued that the development of young children's understanding of the mind can be partially explained by increases in general processing capacity such as working memory.

The results indicated that increases in children's' working memory can contribute to children's acquisition of such concepts as "belief." Unlike the previous theories discussed in this chapter, neo-Piagetian theory supports the notion that children's intellectual development involves domain-general mechanisms. Case (1992), for example, hypothesized that central processing capacity, specifically, *working memory* plays a significant role in the development of children's cognition.

The Role of Working Memory Growth in Cognitive Development

Neo-Piagetians considered the development of working memory as a causal factor in cognitive development (Case, 1974, 1985; Fischer & Pipp, 1984; Halford, 1982, 1993; Pascual-Leone, 1970, 1987). A dominant theme within the neo-Piagetian framework is the claim that working memory both *limits* and *potentiates* the development of cognitive abilities (Case, 1985; Halford & Wilson, 1980; Pascual-Leone, 1970,1988). Although different formulations of working memory have been proposed, what neo-Piagetians had in common was a search for a different construct than the traditional Piagetian logical structures that could account for cognitive development in general. Moreover, there was a search for an underlying mechanism that would support the existence of general cognitive stages. The reason for such a search was due to the problems researchers encountered when they used Piagetian tasks to investigate young children's logical competencies.

As an example, studies conducted by Starkey, Spelke and Gelman (1983) on young children's number knowledge and the task-analysis studies conducted on Piaget's tests by Pascual-Leone (1969) and Fischer (1980) indicated significant problems with test results. The following three areas were particularly problematic:

(1) insignificant cross-task correlations on Piagetian measures assumed to tap the same underlying general structure and that were originally passed by children at the same age;

(2) different measures testing the same underlying construct were passed at very different ages resulting in substantial asynchrony in the rate of development of concepts. For example, children's conservation of weight reached the stage of concrete operations by the age of 8 or 9 years while their conservation of number was achieved by the age of 5 or 6 years and

(3) substantial short-term training effects on logical tasks such as conservation which were assumed by Piaget to be dependent on the gradual emergence of a general operational structure that was impervious to any form of external manipulation.

Although these results did not challenge the epistemological foundations of Piaget's theory, they did run counter to the idea that children's cognitive development was dependent on the gradual acquisition of a universal system of logical operations. As new data were collected and existing data examined in more detail, it became increasingly apparent that children's cognitive processes were far more content, context and culture specific than Piaget had assumed.

Case (1985, 1992) and his colleagues suggested that much of children's intellectual development can be characterized in terms of domain-general mechanisms. Theorists such as Fischer (1980) and his colleagues hypothesized that general stages should be defined in terms of constraints or upper limits (Fischer & Bullock, 1981; Fischer & Pipp, 1984 ; Flavell, 1993). These limits constrain the complexity of the skills children can construct at different stages in their cognitive development. In other words, even under optimal conditions that provide practice, instruction and environmental support, there is an "upper bound" to the level of structure that children can assemble at any age suggesting a stage-like "evenness of functioning" across different tasks where experiential and individual differences are controlled (Case, 1985). These ceilings are a result of the existence of age-related organismic constraints that apply generally across all domains and that change gradually over the course of development (Case, 1978,1985; Collis & Biggs, 1982; Fischer, 1980; Fischer & Canfield, 1986; Halford, 1982; Pascual-Leone, 1970, 1989). It was suggested that these upper constraints are set by limits in information processing capacity, specifically, *working memory* which can explain the nature of these constraints in operational terms. Neo-Piagetians argued that two factors play a central role in determining the upper bound of children's performance on cognitive tasks: (1) working memory growth and (2) operational efficiency within this memory (Case, 1985,1992; Fischer & Pipp, 1984). Consequently, the knowledge structures children are able to assemble at any stage in their cognitive development are determined by their working memory capacity. The next section will introduce one neo-Piagetian model that attempts to embody both the general and specific aspects of cognitive development. This model provided the theoretical framework used in this study to investigate the nature and development of children's understanding of scientific phenomena.

Case's neo-Piagetian Model of Cognitive Development

According to classical Piagetian theory, children's understanding of scientific concepts is analyzed from a structural perspective, investigating the relations between the general logic of the child and the causal explanations he/she gives. While neo-Piagetian theory maintained a structural approach, it also added semantic and syntactic information in describing children's development. One representative of this "school" of research is Robbie Case (1985, 1992, 1996). His model of cognitive development preserved the Piagetian notion of age- and stage-related changes in children's representations of knowledge and articulated the cognitive processes that induce changes in children's conceptual understanding. Maintaining the Piagetian tradition, Case proposed that, in any given content domain, children progress through a series of cognitive-developmental stages, each of which involves a move to a higher level of processing. He also hypothesized that children's conceptual understanding has a distinctive organization or operational structure at each of the following age levels: Infancy, early childhood, middle childhood, and adolescence. Consequently, four major stages are still hypothesized, following the classical Piagetian theory: Sensorimotor (0-18 months), Interrelational (1.5 - 5 years), Dimensional (5 - 11 years) and Vectorial (11 -19 years). Case's four-stage model of development is presented in Appendix A.

As an example, the type of operational thought occurring from the ages of 2 - 5 years is defined by Case in terms of *relational* structures. Children in this stage of interrelational development are able to coordinate, differentiate and eventually consolidate two different forms of relational structures. In other words, children understand a system of relations. A prototypical response of relational thinking in reasoning about buoyancy might be: "If there is a hole in the boat it will gradually sink" or "If an object is heavy then it will sink and if it is light it will float." Children tend to focus on the polar attributes of objects such as "heavy" and "light" or "big" and "small." According to Case (1985,1992), children's thinking at the Interrelational Stage may be characterized as forming relationships between the attributes of objects and their resulting actions. On a balance beam, for example, young children relied on their perceptual judgments of "big" and "small" stacks of weight to make judgments about which side of the balance beam will go down.

Following this cycle there is a qualitative shift from ***relational*** to ***dimensional*** thought commencing at approximately 5 or 6 years. Progression from one stage of development to the next occurs when two qualitatively different conceptual structures or "mental units" are coordinated and consolidated at the end of the previous stage. For example, by the age of 6, children can differentiate and coordinate two relational systems so that some higher-order unit of thought emerges. Regarding children's mathematical knowledge, four-year-olds demonstrate (1) a global sense of quantity which enables them to answer questions about "more" or "less" and (2) an ability to count a set of objects in a set. However, during the preschool years, these two relational structures cannot be integrated yet. As children move from age 4 to age 6, they are able to coordinate the two relational systems so that one quantitative dimension results, that is, a conceptual understanding of the "mental number line." This enables children to conceptualize such variables as "heavy" and "light" in a quantitative manner.

Case (1985, 1992) hypothesized that children from the ages of 5 -11 years are capable of "dimensional" thought. At this stage in their development, children are able to coordinate two different dimensions to provide coherent explanations for quantitative, scientific, social, musical and spatial problems. For instance, when working on problems using a balance beam, children begin to use number to make judgments about two quantitative dimensions - weight and distance from the fulcrum - as to which side of the balance beam will go down. The Balance Beam task was first introduced into the literature by Inhelder and Piaget (1958) who used it to study children's development of the concept of ratio. It was later adapted by Siegler (1978) to study younger children's encoding and integration of quantitative variables. The version used by neo-Piagetians was the one designed by Marini and Case to assess children's scientific reasoning from predimensional through to integrated bidimensional thought in understanding the way in which two opposing dimensions (mentioned above) determine which side the balance beam will go down (Marini, 1992; Marini & Case, 1993).

The next section describes three different dimensional levels of children's problem-solving on the Balance Beam Task from the ages of 6 to 10 years. The transition to more abstract thought which occurs around the age of 12 years will also be included.

Development of children's scientific reasoning on the balance beam task. Numerous neo-Piagetians have used Marini and Case's version of the Balance Beam Task in their studies to assess children's problem-solving skills through middle childhood and adolescence. The results of these studies generally reflect the following developmental pattern of thinking through which children progressed in the Dimensional Stage. Common age-typical patterns of understanding were revealed approximately around the ages of 6, 8 and 10 years which represent the mid-points of the three substages within the Dimensional Stage. The pattern of reasoning exhibited at each age level was consistent with Case's age-related postulates.

As mentioned in the last section, children of five and six are able to use the dimension of number to judge weight. Where, in early childhood (Case's Interrelational Stage), they focused on the polar attributes of "heavy" and "light", they can now think of weight as a continuous variable and can count weights to make judgments about which side of the balance beam will go down. This pattern of thinking is characterized as *unidimensional* thought when children are able to focus on the precise number of weights on each side of the fulcrum as long as the distance is kept constant. By about seven or eight, children can use number to make judgments about two quantitative dimensions - weight and distance from the fulcrum - but they cannot yet integrate these dimensions effectively. Children can predict that, when the weights on either side of the beam are equal, the side whose weights are further from the fulcrum will descend. This pattern of thinking is characterized as *bidimensional* thought when children can notice the second, less salient dimension, that is, distance from the fulcrum. Over the course of time children demonstrate progressively more sophisticated capability in representing these quantitative relations.

By age 10, they can coordinate these dimensions in an integrated fashion and make rudimentary *relative* judgments about how variations in weight and distance affect balance. For example, in problems where the dimensions of weight and distance are put into conflict, 10-year-olds are able to apply addition and subtraction strategies to resolve such problems. Their thinking thus acquires reversibility and compensation (Case, 1985). This pattern of thinking is characterized as *integrated bidimensional* thought.

According to Case's theoretical predictions, a major qualitative shift in children's thinking takes place around the age of 11 or 12. The above quantitative-compensation structure marks the pinnacle of what Piaget labeled "concrete operational thought" and in Case's model "dimensional thought." Twelve-year-olds are able to conceptualize a more abstract dimension; in effect, they no longer focus on two concrete dimensions separately but on the "vector" that results from their opposition. As an example, on the balance beam task, the "vector" or second-order dimensional operation that emerges is the notion of *ratio*, an abstract concept that brings a quantitative comparison to the relationship between the two lower-order dimensions of weight and distance.

Therefore, by the age of 12, children progress to a higher-order level of thinking, that is, from first-order to second-order dimensional operations. Case refers to the latter as *vectorial* operations. *Vectorial* thinking on balance beam tasks involves proportional reasoning of weight and distance. Similarly, proportional reasoning is also required for tasks involving density problems since the dimensions of weight and volume are proportionately related in determining an object's buoyancy. At this point in a child's development, Case's

(1985,1992) final qualitative shift to a ***vectorial*** stage reflects a child's advancement to abstract thought which is similar to Piaget's formal operational thinking.

Recursive and Hierarchical Nature of Cognitive Development

Within each of the four major stages, Case (1985,1992) hypothesized the same recurring structural pattern in the development of children's thought characteristic of each stage (e.g., dimensional). The nature of this recursive cycle parallels the structural changes that took place in children's cognition on the balance beam problem that was described in the preceding section. Case (1985) characterized these developmental changes in children's "dimensional" thought as proceeding through a sequence of three levels or substages from uni-dimensional (6 years), to bi-dimensional (8 years) and finally to integrated bi-dimensional (10 years). Reference can be made above to the general characteristics of thought at each of these levels. Transition from one level of thought to the next was the production of a more sophisticated structural relationship that children demonstrated between the two dimensions - weight and distance when problem-solving on the balance beam tasks. At each of these substage levels, Case explained these structural changes in terms of the differentiation, coordination and eventual integration of these two quantitative dimensions. A structural diagram of this recursive cycle in Case's theory is illustrated in Appendix A.

This structural cycle is recursive because it repeats itself in each of the major stages and is hierarchical because the transition from one major stage to the next involves a move to a higher level of cognitive processing in the sense that a new qualitative form of thinking evolves. Recall, for example, the major change that occurs in children's development between the ages of 10 to 12 years as they move from dimensional (concrete) to vectorial (abstract) thought on the balance beam problems. The process of transition to the next major stage occurs when dimensional structures collapse into a single element which forms the nucleus of a new higher-order structure that Case defines as vectorial - and the entire structural process recycles. Case (1992) conceptualized the development of these cognitive structures along two axes. This structural recursive cycle is represented on the vertical axis along which Case attempted to explain the gradual hierarchical performance variation within each stage as sequentially ordered "substages" that characterize structural levels of thought of increasing complexity as they move up the axis (refer above to dimensional levels of thought).

Development along the horizontal axis represents the application of this vertical progression across different domains of knowledge (e.g., number, social, spatial, narrative). This horizontal axis was conceptualized after a strong similarity in the general form of children's numerical, narrative, and spatial development was revealed between the ages of 4 and 10 years. In each domain, 4-year-olds appear to possess two distinct structures which gradually merge into one new higher-order structure by the age of 6 years. Between the ages of 6 and 10, structural parallels in children's numerical, narrative and spatial cognition were identified that were consistent with the vertical progression that Case (1988, 1992) had hypothesized. The structures differed with regard to their semantic components, that is, their content in terms of meanings, representations, or concepts specific to each domain. What was similar across all three domains was a common structural growth pattern characterized by the increasing complexity of the syntactical relationship between these different semantic components.

Because of these structural parallels noted in children's thinking across domains, Case (1988, 1992) began to revise his theoretical model in an attempt to find an intermediate or middle-level conceptual structure which might help to bridge the gap between the general and local perspectives on cognitive development. However, Case (1986, 1988) and his colleagues sought to balance this theoretical move against centrality by locating general systemic changes in processing capacity limitations that could possibly account for the general synchrony in development across domains. Research findings suggested that increases in the size of children's working memory coincided with the structural changes in their cognitive processing across various domains (Dennis, 1981, 1987; Griffin, 1992; Marini, 1992, 1995; McKeough, 1984, 1986). This led to a new proposition of the theory that took into consideration both general and specific aspects of cognitive development. Case proposed that the recursive structural cycles within each of the four stages of his model paralleled recursive cycles of working memory growth that were age-related biological constraints that apply across the entire psychological system. Hence, children's developmental progression from one substage to the next within each major stage is accompanied by an increase in the size of their short-term storage space (STSS) or working memory while engaged in solving a current problem characteristic of that particular stage. This increase in STSS is assumed to be a function of both maturation and experience. In Appendix A, the working memory demand (noted as W.M.) is given for each structural form of thought. As can be seen in the diagram, working memory demand progresses from 2 to 4 "executive processes" that need to be assembled in order to execute the increasing levels of thought from partial to complete mastery of the cognitive system within each major stage.

A New Direction in neo-Piagetian Theory

After several years of gathering data across several different domains (e.g., mathematical, social, spatial), Case and his colleagues began to discern two significant patterns in children's cognitive growth. This new development was a corollary of the original notion of cognitive development proceeding along two axes simultaneously. The first pattern was similar to the one postulated by researchers working within the modular and knowledge expertise frameworks. The second pattern appeared to be more general in nature similar to Piaget's notion of some type of general cognitive structure. According to neo-Piagetians, what gives development its generality is not the notion of logical structures as suggested by Piaget, but the existence of age-linked constraints on children's information-processing capacity and/or working memory.

In an attempt to bridge the gap between the general and local perspectives on cognitive development, Case postulated the existence of a new construct, namely, the central conceptual structure. He hypothesized that the development of this new construct might help to reconcile conflicting viewpoints between the classical Piagetian perspective and domain-specific theories. More importantly, it might lead to a better understanding of the overall system of cognitive development. By taking this new direction, Case has placed more emphasis on domain specificity while retaining Piaget's core notions of centrality and generality. Case's main objective was to create a theory of intellectual development that occupied a middle ground on the generality/specificity issue. While the content of central conceptual structures are modular or domain-specific, the structures themselves are subject to general systemic constraints and change only gradually with development (Case, 1985, 1992).

Interestingly, this new construct plays a kind of unifying role in the sense that it bears a strong resemblance to one core postulate from each of the different theoretical approaches that have been reviewed in this chapter. For instance, it is similar to the modular notion of a naive "theory" which proposed that, at the heart of children's conceptual systems, is a core set of elements that play a pivotal role in determining the nature of the theories they construct. Central conceptual structures bear a strong resemblance to the notion of "knowledge networks," the way knowledge is organized, structured and integrated in children's conceptual schemes or mental models. Finally, the relevant sociohistoric notion is the "conceptual/linguistic framework" in that the content of children's central conceptual structures becomes increasingly distinctive with age as the development of these structures depend on the conceptual and notational systems of its culture

The Notion of Central Conceptual Structures

Case (1992) posited the presence of a central conceptual structure in children's quantitative, social and spatial thought. A central conceptual structure is an organized set of concepts and conceptual relations which are defined in neo-Piagetian lexicon as "a system of semantic nodes and relations" (Case, 1992; Case & Griffin,1990). It is considered to be the "center" of children's thinking about a given domain, albeit a very broad domain, but does not have a system-wide application. Central conceptual structures are defined as forming the basis of a wide range of specific concepts in a specific domain. Like the "naive" theorists postulated (Carey, 1985), such structures are not applicable to the entire range of children's experience, simply to an experience within a specific domain. The domains are extremely broad ones and transcend what educators or learning theorists normally term "disciplines" or "subject-matter areas."

Case (1996) suggested that such structures are "central" in at least three different ways. First, they form the conceptual "center" of children's understanding of a wide range of situations both within and across culturally defined disciplines or content areas. Second, they describe the core conceptual elements in a domain which lay the foundations for future development in that particular area of knowledge. By the same token, central conceptual structures occupy a semantic middle ground level of generality. Thirdly, central conceptual structures are "central" in that they are constrained by limitations in children's central processing. These general systemic constraints give the structures a different form at different age levels. Moreover, the nature of these structures are such that they possess general commonalities in form that transcend the particular domain to which they apply. The development of central conceptual structures underlying children's quantitative, social and spatial thought has already been articulated in the literature (Case & Griffin, 1990; Case & Sandieson, 1992; McKeough, 1992; Dennis, 1992). In order to more clearly elucidate these hypothesized commonalities of the structures, the central conceptual structures underlying children's quantitative and social thought will be briefly discussed.

Central conceptual structures underlying children's quantitative thought. The central numerical structure underlying children's quantitative thought is the "mental number line" (Case & Griffin, 1990; Case & Sandieson, 1988) which is hypothesized to emerge at around 6 years. Prior to this age, children possess two conceptual schemas regarding the concept of number. First, they are capable of making non-numerical judgments of quantity in the form of "more" or "less" for example. Second, there is evidence to support the notion that preschool children also possess a good deal of knowledge about quantity that is numerical in nature (Starkey, 1992; Case & Griffin,1990). However, these two sets of knowledge typically are not integrated until about the age of 6.

Once the "mental counting line" has been formed, children use this basic knowledge structure as a lens through which they view the quantitative world (Case & Okamoto, 1996). Children use the number line as a tool to create new knowledge and to measure such dimensions as time, space, money, or weight. It is important to mention that the "mental number line" does not simply function as a tool for making sense of the world; it also functions as a "core conceptual element" which Case describes as a central numerical structure that underlies children's quantitative thought.

Between the ages of 6 and 8, children become proficient in using single mental number lines and can tentatively begin relating two mental number lines as they acquire more properties relating to the numerical system. For example, children begin to see the relation between the "tens" column and the "ones" column though this relation is not yet fully understood. With further growth and practice, by about the age of 10 years, the relation between two or more mental number lines is explicitly understood and represented. Therefore, the development of children's central numerical structures is hypothesized to progress through three recognizable phases between the ages of 6 and 10. These phases represent unidimensional, bidimensional and integrated bidimensional levels of thought.

Children's understanding of number has been hypothesized to play a central role in producing the developmental changes that were observed on four different kinds of task, namely (1) tests of scientific reasoning, including Siegler's (1978) Balance Beam and Projection of Shadows task and Noelting's (1982) Juice Making tasks (Marini, 1992); (2) tests of social reasoning including Marini's Birthday Party (1992) and Damon's (1977) Distributive Justice tasks; (3) tests of math applications such as money, time or musical scores and (4) tests of math computation and estimation (Case & Sowder, 1990; Griffin, Case & Siegler, 1994). Performance across all of these tasks was found to be highly consistent at the age-levels of 4, 6, 8 and 10 years. This general cross-task parallel on children's performance corresponded to the age-related theoretical predictions of Case's theory. To account for these findings, Case and his colleagues proposed that each task had some quantitative component and that children's performance across these tasks of distinct content domains could be explained by their growing understanding of number (Case & Griffin, 1990; Griffin, Case & Sandieson,1992). As children mature, their conceptual representation or mental model of their quantitative world becomes more complex. Developmental growth is effected by (1) an increase in children's understanding of the central numerical structure, the "mental number line," which is believed to be potentiated by (2) an increase in the size of children's working memory or processing capacity.

According to neo-Piagetian theory, the notion of a central conceptual structure fills two potentially important roles. First, it shows how children's conceptual understanding is limited by the general developmental changes that take place around 4, 6, 8, and 10 years. Second, it shows how important a role this structure plays in mediating children's performance across a broad range of tasks. In postulating a central conceptual structure, Case (1992) has shifted the locus of generality in children's performance from the size of their working memory to a conceptual structure that is assembled and nested within that memory. In so doing, Case's (1992, 1996) revised model enables researchers to make theoretical predictions regarding the representational complexity of children's mental models at different age levels. Whereas the size of children's working memory constrained performance across any set of tasks, the postulation of a central conceptual structure necessarily restricts performance to a particular task domain, in this case, the domain of number knowledge.

Central conceptual structures underlying children's social thought. Notwithstanding the semantic differences, there is a strong similarity in the general form of children's numerical and social development from the ages of 6 to 10 years. The central conceptual structure underlying children's social thought has to do with children's representation of people's intentions. In effect, this intentional structure may be viewed as a mental "story line" that is similar in form to the mental "number line" which is central to children's quantitative thought. Using Case's theoretical framework, studies were conducted to determine the role of this intentional structure in the development of children's social thought. Tasks were designed to correspond to the age-related theoretical predictions proposed by Case's theory regarding the structural progression in children's thinking at the ages of 6, 8 and 10 years.

Investigations included (1) children's explanations for the meaning of happiness and sadness (Griffin, 1985); (2) children's feelings of empathy (Bruchowsky, 1992) and (3) children's narrative composition (McKeough, 1986; 1992). What the data suggested was that children develop a common central "intentional" structure to interpret each of these social understandings. At the ages of 6, 8 and 10, children's social understanding progresses from uni-intentional to bi-intentional and then to integrated bi-intentional respectively. This progression in social thought directly parallels the corresponding dimensional progression in the domain of number. Consequently, McKeough (1992) and Griffin (1992) suggested that this "intentional structure" may constitute a central conceptual structure in the domain of social cognition.

This hypothesized progression of children's conceptual competencies in these two broad domains between the ages of 4 and 10 years can be summarized as follows. In each domain, 4-year-olds seem to possess two separate knowledge structures and between the ages of 4 to 6 years these structures become integrated forming a higher-order system of operational thinking. This merger often results in the construction of a new central structure that has a "line-like" characteristic (e.g., mental counting or story line). Finally, in each domain, there is a similar structural progression of this central conceptual structure between the ages of 6 and 10. These general characteristics across the domains of number, narrative and space have been summarized by Case (1996) and are presented in Table 2.2.

Table 2.2

Hypothesized Progression in Children's Conceptual Competencies between 4 and 10 Years of Age

General Competence	Manifestation in Domain of Number	Manifestation in Domain of Narrative	Manifestation in Domain of Space
Level 1: Two sets of relations, one linear (A) and one less so (B), can be conceptualized and assigned appropriate symbols	A. Global quantity schema B. Object counting schema	A. Inner state schema B. Event sequence schema	A. Object shape schema B. Object location schema
Level 2: Merging of two schemas into supercoordinate unit, often one with a "line-like" character	Mental counting line	Mental story line	Mental reference line
Level 3: Two superordinate (often line-like) structures differentiated and tentatively related	Two mental counting lines related; e.g., understanding of tens and ones in base-ten number system	Two story lines related; e.g., understanding of two-character interaction; understanding of main story plus complicating events	Two spatial reference axes related; e.g., first understanding of maps, Cartesian grids, and perspective
Level 4: Ability to formulate relations among different dimensions and scales in an explicit fashion as well as to generalize to an entire system	Multiple counting lines related; e.g., understanding of whole number system	Multiple story lines related; e.g., well-integrated action stories	Two or more reference axes related; e.g., understanding of orthogonal layout in maps and perspective in pictures

Note. From "The Role of Conceptual Structures in the Development of Children's Thought," by R. Case and Y. Okamoto, 1996, Monographs of the Society for Research in Child Development, Serial No. 246, Vol. 61, Nos. 1-2, p. 15.

Case and Okamoto (1996) proposed that the reason for such similarities in the form and development of these central conceptual structures across domains may be a consequence of several common factors. They suggested that children experience (a) similar maturational changes across domains during this age range, (b) similar exposure to school experiences and (c) similar motivational factors of natural curiosity which facilitate a child's general conceptual development.

Conclusion

The first section of this chapter began with a brief historical look at how the notion of *mental models* was first introduced into the developmental literature and how this construct has evolved from the Piagetian era to its present day use in educational research. A detailed discussion of the architecture of mental models in terms of representational thought was the main objective of this literature review. The *mental models* of particular interest in this chapter were children's conceptual representations of scientific phenomena. In the next section, I presented three different theoretical perspectives that utilized the construct of mental models to represent children's development of scientific knowledge. Studies in the liteature that investigated children's conceptual understanding of density and other physical concepts were reviewed and critiqued for the purpose of informing this current project's direction and methodology.

A summary of the strengths and limitations of each research inquiry concluded each theoretical discussion. Furthermore, Table 2.1 provided an overall summary of the general postulates of each theory in terms of (1) how the mind was conceptualized; (2) how children's mental models were interpreted and (3) how the process of conceptual change was explained. This enabled the reader to compare the three different interpretations of children's mental models and their development. The final section was devoted to a fourth research inquiry, namely neo-Piagetian theory, in which I attempted to show how this line of inquiry provided a more detailed analysis of children's cognitive development than the previous research inquiries.

Notwithstanding the substantial contribution made by developmental theory in providing different "mental model" representations of the way children conceptualize scientific concepts, what appeared to be lacking in most of the inquiries was some form of consistency in research methodologies and procedures. Although learning theorists and social constructivists attempted to document the development of a specific concept of children of different ages, their techniques and units of anlaysis to define mental models varied considerably from study to study. For example, modular theorists tended to rely on case studies to describe and explain conceptual changes in children's mental models (Carey, 1985, 1988; Fodor, 1982). Alternately, learning theorists and social constructivists used a "snap-shot" method of research to assess changes in children's mental models before and after some type of intervention. Case, on the other hand, designed a developmental model in the form of a continuing framework that enabled researchers to document conceptual changes in children's understanding of a specific concept at various ages levels.

Another caveat that emerged from the literature concerned the use of the construct of mental models. Attempts to articulate both the structural and conceptual changes that occur in children's mental models lacked any form of indepth analysis. Conceptual changes in children's understanding appeared to be the main focus of modular theorists (Carey,1985; Carey & Smith,1993) while the novice-expert researchers essentially analyzed the structural reorganizations in children's knowledge networks (Chi & Rees, 1983). Only neo-Piagetian theory attempted to describe and explain how both of these facets of a child's mental model changed. In order to assemble a more complete picture of children's representational thought, future studies will need to address both the structural and conceptual aspects of children's scientific thinking.

There is already sufficient evidence in the literature of student difficulties in learning particular physical concepts such as heat and temperature or force and motion (Driver et al., 1985; McCloskey, 1983; Watson & Konicek, 1990). Part of the problem was presumed to be due to students' reluctance or possible inability to change their present mental model in favour of the scientific way of explaining such phenomena. This challenging issue of how teaching and learning of complex scientific concepts transpires raises an important question of how to design more effective approaches to teaching science that will facilitate some sort of conceptual change in the learner. Case's developmental theory may quite possibly be able to shed some light on this challenging question. Like all neo-Piagetian theories, both the general and specific features of children's cognitive development are delineated. This enables neo-Piagetians to explain what aspects of a child's understanding can be changed with effective instruction and what aspects, of a more general nature, remain unchanged due to maturational constraints.

The contributions of Case's (1985, 1992) neo-Piagetian model of cognitive development to advancing educational theory and practice in the field of physical sciences are particularly promising. His model enables researchers to articulate the structural and conceptual nature of children's mental models or knowledge representations at various points in their development. Changes in children's conceptual structures at the ages of 6, 8, 10 and 12 years are studied systematically at a fine grain of analysis. In essence, Case's developmental model provides educators with a process approach that articulates children's developing epistemological understanding of a scientific concept. According to Kuhn (1997) and Carey and Smith (1993) children's common sense epistemology of science "strongly influences what sense children are making of the scientific inquiry in which they engage and the subsequent uses they are likely to put it to" (p. 147).

Charting the "natural" developmental path of how children's understanding of a specific concept evolves over time makes it possible for educators to (1) assess children's "entering competence" of a specific concept and (2) set developmentally realistic goals for instruction. The scientific concept chosen for this project is density. Density is a higher-order property of substances and not a property of objects themselves. Such factors make it likely that this concept cannot be truly understood, if at all, until late in development. In order to fully understand the concept, an individual needs to understand proportional reasoning since density (in its formal scientific sense) is defined as mass per unit of volume. In other words, a complete understanding of density is dependent on the ability to integrate the more readily perceived properties of volume and weight. The latter are simpler kinds of scientific concepts referring to one particular entity whereas density is a more complex in that several elements are combined.

However, density has a distinct empirical outcome - buoyancy. The buoyancy of an object is dependent upon the object's density and is a property that can be perceived clearly since young children have a great deal of experience placing objects in water and seeing them either float or sink. Since buoyancy is a property that can be easily perceived, it is therefore plausible to hypothesize that children will have, to some degree, an implicit conceptual understanding of density as it relates to buoyancy. As a researcher and educator, it seems reasonable to adopt a more continuous view of children's development of a scientific concept such as buoyancy. The following research question and hypothesis are intended to guide this developmental study.

Research Question

What is the nature of children's conceptual understanding of buoyancy from the ages of 6 to 10 years?

Hypothesis: Children's conceptual levels of understanding at the ages of 6 years, 8 years and 10 years will correspond to the developmental substages of "dimensional thought" in middle childhood as described by Case (1985, 1992) such that there will be significant age-related differences in level of understanding of causal factors that determine buoyancy.

Rationale

Case (1985, 1992) postulates that children from the ages of 5 to 11 years are capable of "dimensional" thought. At this stage in their development, children are able to differentiate and coordinate different dimensions in increasingly complex ways to provide coherent explanations for scientific problems. Case (1985,1992) proposes a general structural progression of "dimensional" thinking within this age range from pre-dimensional to unidimensional to bidimensional and finally to elaborated dimensional thought. His neo-Piagetian model provides a metric for classifying the level of conceptual operation at each of these substages in terms of their complexity. Children's conceptual structures are hypothesized to become increasingly complex as children develop. Furthermore, Case proposes a major qualitative shift from dimensional to more abstract-dimensional thought, that is, formal reasoning, around the age of 12 years as children progress to the Vectorial (adolescent) Stage of cognitive development.

The following chapter describes the methodology used to test this hypothesis. An outline of the three different research phases to this study will be presented: (1) a classroom-based science unit on buoyancy in which the author was involved, (2) a description of a multilevel task design intended to measure different conceptual levels of understanding of buoyancy and (3) procedures for the administration of the Buoyancy Measure.

CHAPTER 3 : METHODOLOGY

The main goal of the study was to investigate the nature of children's understanding of scientific phenomena in middle childhood. More specifically, the purpose of this research was to determine whether or not there was a developmental sequence in children's understanding of buoyancy across different age levels. Presentation of the method and procedures for this study is organized into three sections: (1) a classroom-based science unit on buoyancy in which the author was involved, (2) a description of a multilevel task design intended to measure different conceptual levels of understanding of buoyancy and (3) procedures for the administration of the Buoyancy Measure.

The purpose of the first phase of the study was to field test Case's (1985, 1992) theory to gain insight into the nature of children's scientific reasoning while working on a science challenge in their classrooms. The challenge involved the construction of a model boat that met specific criteria. Information gleaned from this inductive empirical inquiry helped to provide insight into the general parameters of thought units emerging at the ages of 6, 8, 10 and 12 years and also helped to inform task design for a formal study. Children's responses to a set of general questions about what determines an object's buoyancy suggested an age-related progression in understanding which indicated that scoring criteria for the different age groups could be developed. However, it had yet to be empirically supported that children's understanding changed systematically with age in a progressive manner consistent with neo-Piagetian stages of development hypothesized by Case.

Therefore, the objective of the second phase of the study was to develop a set of buoyancy tasks using a multilevel task design to test this proposed developmental sequence. Different buoyancy tasks of varying levels of difficulty were created to specifically measure the hypothesized different conceptual levels of understanding of buoyancy within the neo-

Piagetian framework.

In the third and final phase of the study, this battery of buoyancy tasks was individually administered to a group of elementary school students to test the structural hypotheses generated in the first phase, namely that there is increasing complexity in children's scientific reasoning that is consistent with the age-level postulates of Case's (1992) developmental model.

Phase 1: Building a Structural Model of Children's Understanding of Buoyancy

The first phase of the study was a classroom-based teaching project in which the author was involved. Its purpose was to investigate the nature and development of children's conceptual understanding of buoyancy. The project was exploratory, focusing on the differences in children's scientific reasoning at the certain critical age levels specified by neo-Piagetian theory (6, 8, 10 and 12 years). First, children were given hands-on experiences on which to construct knowledge. Second, interpretations of their understandings or "mental models" were analyzed. This involved the identification of critical factors offered by the children in their responses to problems regarding buoyancy and the articulation of how these factors were coordinated. Responses were then examined by age to determine commonalities within each age group. Based on these empirical data, a model of development in middle childhood was hypothesized to facilitate the identification of a possible sequence in children's scientific reasoning about buoyancy.

Participants

Participants attended elementary schools in three suburban school districts near Vancouver, British Columbia. The sample of elementary students (N = 92) covered the age range of middle childhood. Three intact classes (1 first grade, 1 fourth grade, 1 fifth grade) from two public schools participated in the study (N = 78) as well as a group of students (ranging in age from 9 to 14 years) from a private school (N = 14). The three teachers from the public schools were informed of the author's interest in learning about children's conceptual understanding of buoyancy at different age levels. Upon request, they volunteered to participate in this initial investigation for her study by agreeing to team-teach with the author a science unit on buoyancy. The author worked in each teacher's classroom for approximately one month during which time she was able to interact directly with the students as teacher-researcher and participant observer. In addition to working with these three teachers in the Public School system, the author volunteered to teach the same buoyancy unit to a group of students (ranging in age from 9 to 14 years) in a private school (N = 14). In this situation, the students voluntarily signed up for my 'Science Challenge Course' as one of their electives. They attended one-hour sessions once a week over one school term.

This science unit was separately conducted in each of the four classrooms. Although a few minor adaptations were made to accommodate for the different age levels, the science unit was essentially conducted in the same manner in each classroom. Following the methodology of Case's (1992) research group, children's responses to problems involving buoyancy were elicited with the objective of building a structural model of children's developing understandings about the concept. The next section provides more details regarding the unit's content and procedures.

Establishing the Experiential Foundation

Because children need experience with a task in order to demonstrate "optimal level" of understanding (Case & Sandieson, 1992; Fischer & Pipp, 1984), children were provided with instructional support and practice in thinking about buoyancy. In this science unit on buoyancy, students were provided with the opportunities to conduct a variety of experiments - both self-initiated and teacher-designed - to develop a conceptual understanding of buoyancy and density. Their main goal was to design a model boat to meet specific criteria. The boat had to float, be "seaworthy" (withstand rain, waves and wind) and be able to carry a minimum cargo of 500 grams. It was introduced with a simulated letter from a freight company explaining that the students had all been hired as boat builders. They were to submit a proposal of a boat design that would have a maximum cargo capacity. These sessions were conducted in children's classrooms during science periods. During this exploratory phase of the study, I team-taught with each of the classroom teachers which allowed me to be both researcher and participant observer.

The first few sessions focused on teacher-designed investigations, but, as the unit progressed, the responsibility of designing and testing hypotheses was transferred to the students. Working individually was an option but the majority of students preferred to work in small groups of their own selection and everyone participated in whole-group discussions. Self-directed activities were encouraged with some guidance from the teacher so students could pursue their own lines of research. The type of contextual support provided by the teachers could be described as "guided discovery" involving stressing consistency in reasoning as children began to accommodate new information into existing schemas. As a teacher-researcher, the author directly interacted with the students through inquiry and sense-making conversations. During such interactions children were encouraged to make predictions and provide explanations for why their boat floated or sank.

At the end of the unit, students filled out a self-assessment sheet of their learning experience. They were asked to reflect on the topic of buoyancy and respond to the following questions:

1. The most important thing I learned about buoyancy was ____________________________

2. The most important things that make a boat float are ____________________________

Six-year-old responses were elicited orally and recorded verbatim while the older students individually wrote their reflections on what they considered to be important factors in buoyancy.

<u>Interpreting Children's Blueprints for Understanding</u>

The first step in analysis of children's responses involved the identification of critical factors offered by the children in their explanations of buoyancy. These factors represent the *semantics* of children's reasoning about buoyancy. They are presented below in the approximate order in which they appeared in children's explanations. That is, the first three were offered in varying combinations as explanations by young children; the last three are more characteristic of older children's explanations.

1. Weight ----- "heavy/light" materials; distribution of weight
2. Shape ------ "boat shapes"; symmetry
3. Substance -------- soft/hard texture, heavy/light "stuff" inside object
4. Size (volume) ------ water displacement
5. Relative weight ---- relationship of the object's weight to the weight of the water.
6. Relative density --- relationship of the object's density to the density of the water.
7. Pressure --- upward force of water; downward force of object; buoyancy offsets

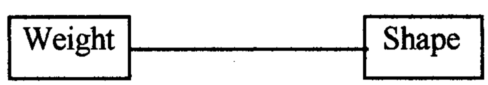
gravity.

The second step in interpreting children's responses involved articulating how children coordinated the factors they offered as explanations; that is, establishing the *syntax* of their scientific reasoning. Case's (1985, 1992) theory and work in scientific reasoning within his theoretical perspective (Marini, 1992) were used as analytic frameworks to build a structural model of children's understanding of buoyancy. That is, a conceptual analysis of children's responses considered (1) the structural or syntactic nature of how children coordinated the critical factors in their reasoning and (2) the conceptual underpinnings or semantics of children's understanding of what scientific factors determine buoyancy.

The developmental period of interest is middle childhood (5 to 11 years). Based on data from this exploratory investigation, hypotheses were generated for conceptual levels of understanding at the ages of 6, 8, 10, and 12 years. The following section describes the proposed developmental sequence.

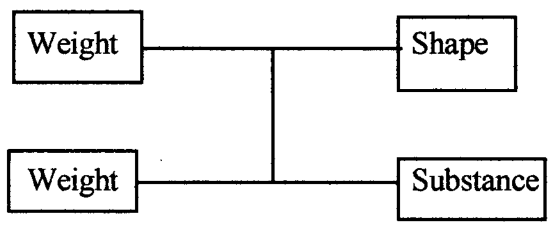
A neo-Piagetian Model of Children's Reasoning about Buoyancy

Substage 1 (5 to 7 years).



Children at this stage of development were hypothesized to focus on weight as a critical variable in buoyancy, coordinating it with another variable (e.g., shape) in a meaningful fashion in terms of how that variable affected an object's weight (Marini, 1992). In so doing, children assembled a "unidimensional" structure in that one variable was used to draw a conclusion about another. For example, a 6-year-old offered the following explanation as to why boats float. "If all the people were on one side, it wouldn't be balanced. Then it would sink. It would sink because it wasn't standing upright. There would be too much weight on that side of the boat." In this example, the variable of "boat shape" or symmetry was coordinated with the dimension of weight to make a judgment about buoyancy.

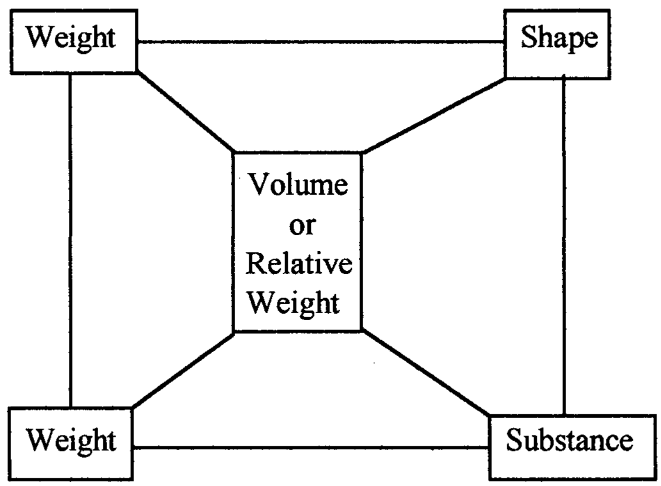
Substage 2 (7 to 9 years).



Although this age range was not represented in this first part of the study, the responses of advanced 6-year-olds and younger less sophisticated 9-year-olds facilitated the link between data and the level of thought hypothesized by Case's (1992) theory for Substage 2. At this substage, children were able to consider two variables as they related to weight in making a judgment about buoyancy, thus thinking in a "bidimensional" manner. Thinking about buoyancy is more well-developed than at the previous level. For instance, "The sides of my boat were even weight so my boat balanced. Boats have thin walls."

Children's judgments about buoyancy become more differentiated from substage 1 thinking by incorporating knowledge about "boat materials" into their notions about weight and shape. In other words, substances or material properties (e.g., Styrofoam, tinfoil, wood) enter into children's explanations and become important factors in assessing an object's weight when making buoyancy judgments. Bidimensional thinking was also demonstrated when considering two aspects of shape as they relate to weight to make a judgment about buoyancy. "It is the way it is made. All you have to do is to make it curved and make the sides high so the water won't get in."

Substage 3 (9 to 11 years).



At this substage, responses were more coherent. Integration and elaboration of the relationship among relevant variables was evident, with the result that responses are characterized as "integrated bidimensional." Children began to show compensation by differentiating between the properties of the boat and the medium (water). "If the boat is heavier than the water you're traveling on, it will sink." At this level, children made an intuitive compensation between variables (Case, 1985). The first notions of volume become apparent at this substage. Although these notions might be described as "naive theories" (Carey, 1985), they represented a higher order understanding of the complexities of buoyancy. "The important things that make a boat float is volume and it has to displace water." "I think the reason my boat did not hold the most weight was because it wasn't the right volume for the weight."

Between the ages of 11 and 13, given the appropriate experience, children can demonstrate a qualitative shift in their thinking from concrete to abstract.

Substage 4 (Vectorial Stage) (11 to 13 years).

Density of boat —— Density of water

This substage represents the beginning of a new stage of development in which children's reasoning abilities are defined by Case (1985) as vectorial. The shift from "dimensional" thinking to "vectorial" is commensurate with a qualitative shift from concrete, operational reasoning to formal, abstract reasoning. This transition becomes apparent when children's thinking about buoyancy progresses to the notion of pressure between the downward force of an object and the upward force of the water. For example, one student commented: "Buoyancy helps the boat float because when the boat pushes downward the water pushes upward." Responses such as this one clearly provide dynamic explanations that focus on integration of elements and relative conditions. Consider the following response made by one student when he was adding "cargo" (i.e., gram weights) on to his boat: "The boat will go lower in the water until it is the same weight as the water. The extra water will be displaced to the side of the boat." Responses become more dynamic and abstract in their reasoning in contrast to the static explanations of Substage 3 that focused on the properties of the object (boat) and the medium (water) as two separate entities.

Buoyancy is now considered in more abstract terms. The density of the boat is related to the density of the water (i.e., relative density). This may be expressed in terms of proportional reasoning: weights of equal volumes of substance and water. Children no longer focus on concrete dimensions separately but focus on the vector that results from two dimensions being in opposition, that is, object and medium. As children acquire this new type of thought, they begin the construction of progressively more complex understandings anew, cycling through three substages of development.

Discussion

The purpose of this first phase of the study was to examine children's scientific reasoning from the ages of 6 to 12 years and to see if it might be possible to hypothesize an underlying structural progression in children's understanding of buoyancy that was consistent with Case's developmental model. The results of this exploratory study were encouraging in terms of identifying conceptual differences in children's scientific reasoning at the certain critical age levels specified by neo-Piagetian theory (6, 8, 10 and 12 years). Children's scientific knowledge was observed to undergo developmental changes. Younger children's associations between the factors determining buoyancy tended to be limited and more idiosyncratic, more perceptual in nature and less structured than those of older children. Older children's conceptual representations included more critical variables and more connections were made between variables. From an analytic point of view, the above hypothesized developmental sequence may quite possibly capture a general perspective of children's scientific reasoning in the sense that it follows a similar structural progression as was observed in other studies investigating children's social and spatial thought. That is, conceptual understanding was age-related and hierarchical, consistent with theoretical predictions (Case, 1985, 1992). Furthermore, a "dimensional analysis" of children's scientific reasoning appears to be quite appropriate in helping to predict age-related conceptual understandings of a scientific concept. Case's developmental model enables educational researchers to conduct a detailed analysis of the structural and conceptual changes that occur in children's representation of scientific knowledge at various points in their development.

The main goal of the next phase was to test the validity of this proposed developmental sequence. Despite the fact that this study was exploratory, it was also theory-driven in the sense that I was actively looking for a particular form of structural progression in children's scientific reasoning that would fit the general schema of Case's (1992) developmental model. Therefore, it is quite possible that the above analysis represents a structure which I simply "read in" in accordance with the theory but which at the same time may have little psychological (construct) validity. With this in mind, a multilevel set of buoyancy tasks of varying complexity was designed to test the age-related theoretical predictions of Case's neo-Piagetian model in order to confirm the hypothesized developmental sequence of children's understanding of the concept.

Phase 2: A Multilevel Task Design

Using the information acquired in the pilot project, an assortment of "naturalistic" problems relating to buoyancy was generated. The tasks were similar in nature to what children might encounter in school science or in their everyday experiences, for example during experimental play. The complete battery of tasks consisted of 20 different items. Four buoyancy problems were designed for each of five developmental levels (see below), on the basis of the theoretical analyses described in the first section. Recall that only four levels were defined in the exploratory study. I included a fifth level in the set of tasks to serve as a basal, the assumption being that all students would successfully perform at this basic level of reasoning. This basal set of tasks also provided children with an opportunity to practice their reasoning skills and begin articulating what they believe determines an object's buoyancy.

The tasks involved objects of different weights, shapes, sizes, substances and densities; factors which were identified as critical in children's reasoning about buoyancy. Throughout the battery, these critical factors were treated either as variables or held as a constant across the five different levels of buoyancy problems. In keeping with a multilevel task design, each task systematically increased in difficulty, placing greater demands on a child's working memory capacity in terms of amount of information to consider when making buoyancy judgments. For instance, pairs of objects pitted the properties of size, weight and density against each other. The following section gives a detailed description of the set of 5 buoyancy tasks that were individually administered to each participant in the third phase of the study.

The Buoyancy Task Measure

Task 1 : Predicting buoyancy based on one factor. The purpose of this task was to establish a basal level in children's understanding of buoyancy. It was hypothesized that the majority of participants would pass this first level task with the possible exception of a few six-year-olds who were not yet able to consider more than one factor in determining buoyancy. Children were presented with four different objects one at a time. They were asked : Will this fool's gold (cork, soap, plastic ball) float in the water ? Why do you think so? By asking these questions, students were required to predict whether an object would float or sink and to support their prediction with an explanation. Acceptable explanations for this first task required children to identify only one factor that determined each object's buoyancy (e.g., weight) and so all critical factors were treated as variables for possible consideration. In accordance with the theory, buoyancy judgments based on one critical factor, such as weight, are characterized as predimensional responses.

Theoretical predictions. Case (1985, 1992) proposes that predimensional thought is characteristic of most 4-year-olds. At this stage in their development, children are unable to conceptualize weight, size and volume in terms of quantitative dimensions. They tend to represent variables such as weight and size in a global or polar manner (i.e., heavy or light; big or small). Although this age range was not represented in the pilot study, the responses of less sophisticated 6-year-olds suggest that, at this substage, reasoning about buoyancy would be limited to only one of the critical factors that determines an object's buoyancy, specifically its weight. This level of thinking is defined as predimensional and serves as the *basal* level for the set of buoyancy tasks.

Task 2 : Predicting buoyancy based on the coordination of two factors (one dimension). The purpose of this second task was to test for the effects of shape on an object's buoyancy. For this set of buoyancy problems, children need to consider at least two factors in their reasoning when making predictions. It was hypothesized that children would focus on weight as a critical variable and then explain how the shape or size of an object affects its weight and buoyancy. Children were presented with the following pairs of objects, one pair at a time.

Items 1 - potato and porcelain oval bowl

Items 2 - metal hat and coin (Mexican peso)

Items 3 - ball of foil and foil in a boat shape (equal amount of tinfoil)

Items 4 - wooden solids (cylinder and pyramid)

For items 1 to 3, children were asked: Which of these two objects will float? Why do you think so? The weight of the paired objects remained constant while shape, size and density varied. By asking these questions, students were required to compare the two objects, keeping in mind that they were of equal weight, and then decide which one would float. Their prediction was to be supported with an explanation. For item #4, each student was informed that the wooden objects would either both float or both sink. Children were asked: Will these two objects float ? Why do you think so? Weight, size and density of the two solids were held constant while shape varied.

Theoretical predictions. By the age of 6 years, most children are hypothesized to assemble a "unidimensional structure" in that they focus on one particular dimension and use it to compare or coordinate with one other variable. Based on the data from the pilot study, it appears that most 6-year-olds draw upon the factors of weight, size or shape in varying paired combinations as explanations for an object's buoyancy. Therefore, to test this underlying conceptual structure the weight of different pairs of objects was held constant while shape, size and density varied. Hence, children were required to relate another factor to weight in a meaningful way to determine which of the two objects would float. In other words, children needed to explain how another variable such as shape or size offsets an object's weight and determines buoyancy.

Therefore, **unidimensional thought (5 to 7 years)** may be delineated as :

weight as a critical variable + a variable affecting weight

(i.e., one dimensional structure)

Task 3 : Predicting buoyancy based on the coordination of three factors (two dimensions varied). The purpose of this third task was to specifically test for the effects of substance and size on an object's buoyancy. For this set of problems, children needed to consider three factors in their reasoning when making buoyancy predictions. It was hypothesized that children would explain how an object's weight and consequently its buoyancy is affected by its substance and size. Children were presented one at a time with the following four critical pairs of objects that pitted the properties of substance weight and density against each other. The questions were the same as Task 2.

Critical Pair 1 : carrot and parsnip

Critical Pair 2 : orange and beet

Weight and shape were held constant while size, substance and density varied.

Critical Pair 3 : sugar cube and wooden block

Critical 4 : tennis ball and marble

Shape was held constant while size, substance, weight and density varied.

Theoretical predictions. By the age of 8 years, most children are hypothesized to assemble a "bidimensional structure" suggesting that two dimensional structures or two sets of relationships between variables can be simultaneously considered and coordinated. Based on the findings in the first phase of the study, it appeared that most 8-year-old children would be able to incorporate a third variable into their reasoning about buoyancy. They begin to make substance comparisons when making buoyancy judgments. In this proposed 8-year-old structure, it is hypothesized that three variables can be interrelated in a "bidimensional" manner. Therefore, **bidimensional thought (7-9 years)** may be delineated as : ***weight as a critical variable + 2 variables affecting weight***

(i.e., two dimensional structures)

Task 4 : Predicting buoyancy by relating an object's weight to the weight of the medium (different liquids). The purpose of this fourth task was to test an object's buoyancy in two different liquids. In order to do this, children needed to make a direct relationship between the object and the media. In other words, children were required to individually compare the object's weight/density to each of the liquid densities as well as make a comparison between the two liquid densities themselves. There was sufficient evidence in the first phase of the study to suggest that older children began to show compensation by differentiating between the properties of the object and the liquid medium when considering an object's buoyancy.

Children were presented with two identical containers of equal amounts of liquids. One container held ordinary water and the other held salt water. Children were clearly able to differentiate between the two liquids. Four different objects were then given to them one at a time. Children were asked : Will this egg (grape, rosewood, lime) float in water or salt water ? Why do you think so? In these tasks, objects remained constant but the liquid media varied.

Theoretical predictions . Reasoning at this level required elaborated bidimensional thought which was hypothesized to be characteristic of 10-year-olds. Like the previous level, two coordinated dimensional structures are present but the relationship between the variables is now represented in a more integrated and elaborate fashion. For instance, it became apparent in the pilot study that children around this age level begin to form a higher-order relationship between the dimensions of size and shape by integrating these two dimensions into one dimension: the notion of an object's volume.

At the bidimensional level, children often encountered difficulty when confronted with problems where objects differed in both weight and shape, forcing them to choose between the two dimensions when making a buoyancy judgment. What children usually do as a consequence is simply to fall back on weight as the basis for prediction. This of course often leads to failure. Although weight, shape and material were coordinated, they were never related *directly* to each other which sometimes led to incorrect predictions.

At this fourth substage, children become aware of this problem and no longer base their decisions entirely on weight when weight, shape and density are in conflict with each other. They begin to develop compensation strategies in order to solve this dilemma.

Elaborated bidimensional thought (9 -11 years) may be delineated as :

Compensating between object and medium properties

(i.e., integration of two dimensional structures)

Task 5: Understanding relative density of object and medium. The purpose of this task was to establish a ceiling level in children's understanding of buoyancy. It was hypothesized that the majority of participants would fail this buoyancy problem with the possible exception of a few 10-year-olds who were able to explain buoyancy in more abstract terms by way of differentiating between the variables of weight, volume and density of both object and media. Children were presented with two sets of two different objects of varying density and two containers of different liquid densities. Children were told that one of the objects would float on both liquids while the other object floated on one. They were asked to predict which of two objects would float on both liquids and to justify their predictions.

Critical Pairs 1 : cranberry/blueberry; oil/salt water

Critical Pairs 2 : rubber duck/kiwi ; salt water/molasses

With these two tasks all critical factors that determine buoyancy are treated as variables.

Theoretical predictions. Vectorial thought represents the beginning of a new stage of development in children's thinking and serves as the ceiling level of this battery of buoyancy tasks. Between the ages of 11 and 13, Case (1985, 1992) proposes that, given the appropriate experience, children demonstrate a qualitative shift in their thinking from concrete to more formal, or "vectorial," thinking. Children no longer focus on concrete dimensions separately but begin to coordinate two dimensions that are in opposition and focus on the vector that results from this coordination. For example, in the pilot study, some 12-year-olds were able to simultaneously consider the density of both the object and the medium which suggests that they are capable of understanding the notion of relative density, the resulting vector of this coordination.

Based on information from the pilot study, buoyancy is now thought of in more abstract terms of relative density or the notion of force between object and medium. At this level, children's thinking is qualitatively different from dimensional thinking in that explanations are more dynamic, focusing on the integration of properties of the object and medium and their relative conditions (i.e., relative density or relative weight of object and medium). **Vectorial thought (11-13 years)** may be delineated as:

density of object + density of medium

a formal understanding of density (density as mass per unit of volume) -

proportional reasoning between weight and volume

Discussion

Once the battery of tasks had been assembled, it was important to field test the measure and check the construct validity of the multilevel task design. The most important objective was to test whether task complexity corresponded to the expected level of reasoning required to pass the task. A small sample of students representing the ages of

4 , 6, 8, 10 and 12 years volunteered to take an "abridged version" of the Buoyancy Measure which included two items selected from each of the five task levels. Volunteers were interviewed individually in an informal situation.

During the pilot interviews, it became quite evident that the use of different types of probes were crucial in eliciting children's "optimal level" of understanding. As a result a list of effective probing questions or statements was developed specifically to elicit children's "best" responses while engaged in thinking about what determines an object's buoyancy. Allowing time to handle and examine the different objects closely prior to making a buoyancy judgment provided students with hands-on experience while thinking about what determines buoyancy.

It was also interesting to administer the tasks to two 12-year-old students even though this age-level was not included in the final study. The nature of their explanations clearly reflected a basic understanding of density by referring more specifically to substance properties rather than to the object's weight per se. Factors of weight, size and volume were used in an integrated fashion to compare the densities of object and medium. In fact, one 12-year-old's level of reasoning was clearly abstract and he was the only student in the pilot sample to pass all five buoyancy tasks.

The data collected from these pilot interviews suggested that a "dimensional analysis" could be one way of predicting age-related performance in children's scientific reasoning about what determines buoyancy. Some minor adjustments were made to refine the "critical pairs" tasks. For instance, a few objects were replaced by more suitable ones to ensure a strong contrast between the "critical pairs of objects." One "candle" task was eliminated from the battery mainly because it brought in an extraneous variable, specifically a linear attribute, which confused children's thinking when making a buoyancy judgment.

In summary, the overall findings of the pilot testing indicated that children's level of performance on the tasks did vary according to age. The buoyancy problems did appear to become increasingly more complex for the students to solve which confirmed the multilevel task design's construct validity. In addition, the complexity of each task appeared to match the intended level of reasoning for which it was designed. It was confirmed that scoring criteria for each level could be developed and that the battery of tasks would be able to measure the conceptual level of each individual's understanding of buoyancy within this developmental framework. Therefore, this set of five tasks was officially assigned to assess the above different operational levels of thinking specified by Case's (1985, 1992) theory for the "dimensional" stage.

Scoring criteria for each level were developed after the measure was administered and are presented in detail in the next chapter.

Phase 3: Testing the Structural Hypotheses of the First Phase

Participants

Participants attended a large elementary school in a suburban lower-middle class district near Vancouver. The school enrollment was approximately 500 students with several divisions for each grade. A total of sixty children who were predominantly Caucasian and ranging from 6 to 10 years were randomly selected using a stratified random sampling procedure. Sex and age were the two factors considered for student selection. The sample consisted of 20 six-year-olds, 20 eight-year-olds, and 20 ten-year-olds, with each age group evenly divided by sex. Consistent with other studies conducted within the Caseian framework, a representation of twenty students for each age group was decided upon as a respectable sample number to test the proposed developmental sequence of children's understanding of buoyancy. Descriptive statistics are presented in Table 3.1. The mean age is calculated in months for each age group.

Table 3.1

Descriptive Statistics for Age Groups

Age Group	6-year-olds	8-year-olds	10-year-olds
n (m, f)	20 (10, 10)	20 (10, 10)	20 (10, 10)
M	78.55	103.70	126.70
SD	3.39	3.37	3.48

Prior to commencing the study, a letter requesting parental consent was sent home with all students selected (see Appendix B). Written parental permission was required for each student's participation in the study. In addition, the researcher asked each student for verbal assent to participate. A transcript of the researcher's request for each student's participation in the study is in Appendix C.

The Buoyancy Measure was individually administered to students between February and May of 1998. The study was conducted at the school in a small room fairly central to the classrooms.

Procedure

Administration of the buoyancy tasks. The complete Buoyancy Measure was individually administered to each participant in an interview situation. These interviews were modeled after Piaget's (1965) clinical method of "informal conversations" The main intention of such informal "conversations" was to reveal the nature of children's thoughts about specific phenomena (e.g., buoyancy). In order to standardize procedures, all sixty interviews were conducted in essentially the same manner by the author herself. All participants were individually administered the 20 task items in the same order. No specific time limit was imposed on the duration of the test; time of administration varied with each student. The average time taken to complete the five tasks was approximately 40 minutes.

At the beginning of each interview, each participant engaged in friendly conversation with the researcher to not only establish rapport but to also explain the purpose of the study. It was crucial to establish from the very beginning that the battery of tasks constituted a non-evaluative activity. The following statement provides a general outline of what was articulated to each student.

Setting the Stage. Each participant was given the following introductory statement prior to doing the set of buoyancy tasks.

The interviewer:

" Thank you for agreeing to work with me on this project. I am looking forward to you sharing your ideas about why you think some objects float in liquids and others sink. The kinds of tasks you do today will also be done by other children of the same age. I want you to do some experiments on objects to see if they will float or sink in water or in some other kinds of liquids. In fact, I want you to do what scientists do. They test out their ideas by conducting different experiments to see what happens. Before we begin let's practice with these objects to see whether they float or sink in this tub of water."

Practice Session. Prior to the presentation of the tasks, each student was given a warm-up period that enabled the researcher to confirm that the meanings of the terms **"sink"** and **"float"** were understood. Each participant was given time to experiment freely with a variety of objects. At the same time, students were given the opportunity to practice the following task procedures with objects not used in the Buoyancy Task Battery.

1. First of all, examine each object closely. You may handle the object if you like and then tell me whether you think this object will float in this tub of water.
2. Once you have made up your mind, I will ask you to tell me why you think so. I'm going to record your ideas on this tape-recorder so that I will be able to listen to them later.
3. Then just as scientists do, you will be able to test your prediction by putting the object into the water.
4. If the object doesn't do what you expected it to do, I want you to come up with a reason as to why you think this happened. Sometimes, experiments don't always work out the way scientists think they will so they too have to come up with ideas to try and explain why this happens. This is what science is all about - testing out our ideas about floating and sinking.

Following this short practice session, the interviewer began administering the actual Buoyancy Measure. The procedure for each task was as follows:

1. Children were given the opportunity to handle and examine the object closely.

2. Children were then asked to make a prediction and explain why they thought that object would float.

There were two question formats in this battery of tasks: " Will this object float? Why do you think so?

On the critical pairs tasks, children were asked to **decide** which of the two objects would float and to justify their predictions. " Which of these objects will float? Why do you think so?"

3. Following this, children tested their predictions by putting the object into the water.

4. Whenever predictions proved to be incorrect, children were asked to suggest a reason for this unexpected outcome. Question: "Why do you think it sank/floated?"

During the interview session, student responses to each buoyancy problem were tape-recorded and subsequently transcribed verbatim on to a protocol sheet (see Appendix D). The different probes used to support children's justifications for their predictions were also recorded and transcribed. The probes were characteristic of socratic-questioning techniques, for example:

" Tell me more."
" Why do you think that?"
" What makes it heavy/light?"
" What do you mean by ___?"
" Is there any other reason?"

Scoring System

Once the battery of tasks had been administered to all sixty children, the next step was to develop an objective scoring system that could be used to assign children's responses to one of the five developmental levels of reasoning that were preestablished in the first phase of the study. A detailed description of the scoring criteria that were developed for each of the five sets of buoyancy problems is presented in the next chapter. Children's responses to each of the 20 items were awarded two scores: (1) a Performance score indicating a pass or fail on each problem and (2) a Developmental score that assessed the level of reasoning reflected in each explanation for what determined an object's buoyancy.

1. <u>Performance score</u>. Children's responses to each problem were scored as correct or incorrect on the basis of their explanations as well as their predictions. A passing score of 1 was assigned to each problem with a correct buoyancy prediction that was supported by the minimum required level of reasoning for what determined the objects' buoyancy. A score of 0 was assigned to problems with incorrect buoyancy predictions based on inaccurate justifications.

Therefore, the success criterion for each of the 20 problems was a correct buoyancy prediction coupled with an appropriate justification that reflected the level of dimensional thinking that each task demanded. In other words, children had to demonstrate, by way of relevant justification, that their buoyancy prediction was not simply a guess but was the result of a genuine attempt to think about the problem at the level in question. The levels of reasoning required to pass each task are specified in the next chapter.

Each child's performance on the five different tasks was then evaluated. In order to pass each task level, students needed to achieve a criterion of 75% (3 out of 4 items correct) within each level. An overall performance score was then assigned to each student protocol representing the number of task levels successfully performed by that particular participant.

2. <u>Developmental score.</u> This score reflected the child's general developmental level of understanding of buoyancy according to neo-Piagetian research predictions. Children's explanations for their buoyancy predictions on all 20 items were each assigned one of the following scores according to the developmental criteria it met.

If level 0 (predimensional thinking) is demonstrated score 0

If level 1 (unidimensional thinking) is demonstrated score 1

If level 2 (bidimensional thinking) is demonstrated score 2

If level 3 (integrated bidimensional) is demonstrated score 3

If level 4 (univectorial thinking) is demonstrated score 4

The results of the study are based on qualitative and quantitative analyses of children's understanding of buoyancy. Chapter 4 will focus entirely on providing a detailed conceptual analysis of children's responses to the problems on the Buoyancy Measure. This will include a brief review of how children's explanations are interpreted from a "dimensional" perspective and assigned a score. A dimensional analysis is simply one way of explaining children's understanding of the concept and appears quite appropriate in testing the proposed developmental sequence in children's understanding from the ages of 6 to 12 years. Many examples of children's responses will be incorporated into the discussion to illustrate the various levels of reasoning on all five task levels. The results of the Interrater Reliability are presented in the next chapter following the description of the scoring criteria for each level. Statistical analyses of the children's scores will be presented in Chapter 5.

CHAPTER 4: SCORING

The objective of the first phase of this study was to conduct an informal investigation into the nature and development of children's conceptual understanding of buoyancy. The results of this classroom-based inquiry suggested an age-related progression in understanding. Furthermore, the research findings were encouraging in that conceptual changes were observed to occur around the age levels of 6, 8, 10 and 12 years. In other words, these hypothesized developmental changes in children's understanding of buoyancy were consistent with the age-level postulates of Case's (1992) theoretical predictions. Younger children's associations between the factors determining buoyancy tended to be limited and more loosely coordinated than those of older children. Older children usually considered more factors and made more elaborate connections between these factors than their younger cohorts.

Conceptual differences in understanding could be identified by (1) the number of factors used to explain an object's buoyancy (2) the choice of factors and (3) the level of complexity in the coordination of factors. This analysis indicated a possible developmental sequence in children's understanding with conceptual changes occurring at approximately 6, 8 and 10 years. According to Case's developmental theory, these ages approximate the points in time when conceptual changes are predicted to occur in children's understanding of buoyancy.

In summary, the results of this first phase of the study suggested an age-related and hierarchical progression in conceptual understanding that was consistent with the age-level postulates of Case's (1992) developmental model. Case's (1985, 1992) theory and work in scientific reasoning within this theoretical perspective (Marini, 1992) were used as analytic frameworks to build a developmental model of children's understanding of buoyancy from the ages of 6 to 10 years.

Conclusions were also drawn from this empirical data that a "dimensional" analysis of children's reasoning about buoyancy could be used to facilitate the identification of a possible sequence in children's understanding across the different age groups. Such an analysis examines the structural and conceptual changes that occur in children's thinking about the concept at these various points in their development. It is this type of interpretation of children's understanding of a scientific concept (i.e., buoyancy) that is used to provide a base upon which an objective scoring system was developed to measure children's performance on the Buoyancy Measure. This being the case, it is first important to operationally define what is meant by conducting a dimensional analysis on children's explanations for what determines buoyancy.

A "Dimensional Analysis" of Children's Explanations

To assess a child's level of understanding of buoyancy, scoring criteria were based on a "dimensional analysis" of children's reasoning for what determines an object's buoyancy. A dimensional analysis of children's conceptual understanding of buoyancy considered (1) the conceptual underpinnings of children's understanding of what scientific factors determine buoyancy and (2) the structural level of reasoning in terms of how children coordinated these critical factors. The first step in the analysis was to identify the number of critical factors (e.g., weight, substance, size, shape, density) offered by children in their explanations of buoyancy. These factors represent the *semantics* of children's understanding of the concept. The second step in the analysis was to articulate the structural level by which the factors were coordinated.

From the ages of 5 to 11 years, Marini (1992) hypothesized that children are able to coordinate increasing numbers of dimensions to provide coherent explanations for scientific problems. Recall that for a response to qualify as "dimensional," a buoyancy judgment must be based on the coordination of at least two factors and these factors must be coordinated in a meaningful way. Theoretical predictions based on Case's (1992) model helped to generate the levels of reasoning for each age group. The proposed levels of reasoning about buoyancy go from predimensional to unidimensional to bidimensional and to integrated bidimensional. This developmental pattern of thought is hypothesized by Case to represent the conceptual levels of thinking across the ages of 4, 6, 8 and 10 years respectively.

In accordance with the theory, different levels of reasoning were determined by the number of varied dimensions articulated in each explanation. Recall that the presence of one dimension, that is, the coordination of two factors, represents unidimensional reasoning; two varied dimensions, that is, the coordination of three factors, represent bidimensional thinking and when these two dimensions are represented in a more integrated manner by way of compensation between object and medium, the response is classified as integrated bidimensional. Articulating the complexity of the coordination of the critical factors establishes the *syntax* of children's scientific reasoning. Hence, a dimensional analysis requires the articulation of the semantic and syntactic nature of children's reasoning for what determines an object's buoyancy.

The main purpose for designing and administering the Buoyancy Measure was to provide a more rigorous empirical demonstration that children's understanding changed systematically with age in a progressive manner consistent with neo-Piagetian stages of development hypothesized by Case (1992). Although my classroom-based research findings were of interest in their own right in terms of providing instructional guidelines for science teachers, the proposed developmental sequence had yet to be empirically supported. This lack of validity provided impetus to conduct a more formal investigation that used a measure to test whether the hypothesized developmental changes in children's understanding of buoyancy were consistent with the age-level postulates of Case's (1992) theoretical predictions. The battery consisted of multilevel tasks specifically designed to assess children's movement from predimensional through to abstract thought in understanding the way in which opposing factors such as weight, shape, size, volume and density can affect an object's buoyancy. The following chart summarizes the minimum level of dimensional reasoning required to successfully pass each of the five Buoyancy Tasks. It articulates the number of factors that need to support a buoyancy judgment at each task level and gives examples of the most common coordination of factors used to provide an appropriate justification for what determined buoyancy:

Task	Minimum Level of reasoning	Prediction based on # of factors	Prototypical Reasoning
#1	0 (predimensional)	1	heavy or light (weight)
#2	1 (unidimensional)	2	2 shape attributes coordinated or weight + shape
#3	2 (bidimensional)	3	weight + substance + air inside or weight + substance + size
#4	3 (integrated bidimensional)	3 (integrated)	object's weight + substance + weight comparison of liquids Compensation between object & medium

#5	4 (vectorial or abstract)	2 (abstract)	density = weight per unit of volume relative density of object & liquid i.e., weight comparison of equal volumes of object & water proportional reasoning

Scoring Children's Responses on the Buoyancy Measure

Once the buoyancy measure had been administered to all sixty participants, an objective scoring system was developed that would assess (1) the number of tasks that each child passed on the Buoyancy Measure which represents a *performance score* and (2) the level of understanding of buoyancy that each child demonstrated on the measure which represents a *developmental score.*

Scoring Procedures

Children's responses to each of the 20 buoyancy items on the measure were assigned two scores. Each item was awarded a Performance Score of pass or fail and a Developmental Score that reflected the level of understanding in the justification.

1. Performance score. 1 = Pass 0 = Fail To pass each buoyancy problem, children were required to make a correct buoyancy prediction combined with an *appropriate* justification that demonstrated the minimum level of understanding demanded by the task. A passing score of 1 was assigned to each task item that met this criteria. Refer to the chart above for the expected level of thought required to pass each Buoyancy Task. Item responses that provided a correct prediction and an explanation that reflected a **higher** level of reasoning than what was required also received a passing score of 1.

A score of 0 was assigned to problems with incorrect buoyancy predictions based on inaccurate justifications. If a correct buoyancy prediction was supported by an explanation that did not meet the required level of reasoning demanded by the task, a failing score of 0 was assigned.

Therefore, the success criterion for each of the 20 problems was a correct buoyancy prediction coupled with an appropriate justification that reflected the minimum level of dimensional thinking that each task demanded. In other words, children had to demonstrate, by way of relevant justification, that their buoyancy prediction was not simply a guess but was the result of a genuine attempt to think about the problem at the level in question. A peformance score reflects a child's level of scientific reasoning on each buoyancy problem.

Criteria for passing each task level. Each child's performance on the five different tasks was then evaluated. To pass each task level, a minimum level of reasoning combined with a correct buoyancy judgment on 3 out of the 4 items was required. In other words, children needed to achieve a criterion of 75% (3 out of 4 items correct) within each level. An overall performance score was then assigned to each child's protocol representing the number of tasks successfully performed by that particular participant.

2. Developmental score. The second score awarded to each item on the measure reflected the type of dimensional structure (e.g., unidimensional, bidimensional) that characterized children's responses for what determined an object's buoyancy. To obtain this score, buoyancy predictions were not taken into consideration. The main focus of interest was to assess the structural level of dimensional thought that children were capable of demonstrating in their explanations of buoyancy even if they were not scientifically correct. The scoring criteria (described in detail in Chapter 3) were used to rate each of the 20 justification responses on the task-battery. They reflected the levels of structural complexity hypothesized by Case (1992). In other words, a developmental score corresponded to the dimensional level of reasoning that was used in each child's justification (whether correct or incorrect) for what determined buoyancy. Recall that:

Level 0 (predimensional) explanations are scored as acceptable if an object's weight or size is mentioned in global terms (i.e., heavy or light; big or small). **Score = 0**

Level 1 (unidimensional) explanations are scored as acceptable if children consider not only an object's weight but also one other factor (e.g., shape, size or substance) when making a buoyancy judgment. **Score=1**

Level 2 (bidimensional) explanations are scored as acceptable if children consider the effects of of two factors on an object's weight. Substance properties are usually considered in terms of texture or the presence of air inside. **Score = 2**

Level 3 (integrated bidimensional) explanations are scored as acceptable if children compare and contrast the differences between (contrast) the properties of both object and medium in a quantitative manner (e.g., The boat-shaped foil is probably lighter for the water because the tin foil is all spread out. (How will that help?) Maybe the more expanded it is the thinner the tinfoil is so it's lighter for the water.) **Score= 3**

Level 4 (Vectorial) explanations are scored as acceptable if children demonstrate a formal understanding of density in terms of proportional reasoning between weight and volume. **Score=4**

Most buoyancy justifications were awarded one of the above scores. However, there were some responses in which the level of understanding appeared transitional, halfway between one level and the next. When a response reflected being in a transitional stage, an intermediate score was awarded .

Intermediate scores. On completion of the first round of scoring the protocols it was concluded that some buoyancy justifications did not exactly fit the criteria of any one of the above five categories. The level of reasoning in such responses seemed to go beyond one category but failed to qualify at the next higher level. These responses received an intermediate score of either 1.5 or 2.5 and were classified as transitional in the sense that the level of reasoning appeared to be transitional in terms of moving from one level of reasoning to the next higher level. So if a response met all the criteria for one level and some but not all of the criteria at the next level, it was scored halfway between the two. A score of 3.5 was not assigned to any response as the area of interest in this study is from the ages of 6 to 10 years and also because very few participants were able to reason beyond level 3.

A score of 1.5 was assigned to a response that met all the criteria for unidimensional thought and some but not all of the criteria for bidimensional thought. For example, to qualify for this score, three factors were considered to affect an object's buoyancy but only two of the factors were related to each other. A third factor was mentioned but not justified why it offset the others.

Example: "The orange will float because you can squish the orange easier than the beet and there's juice and probably some air." (boy, age 6) **Score =1.5**

whereas

Example: "The beet will sink because it feels hard and has no air inside it. And the orange will float because it has little pockets of juice and air inside it. There's some squishy parts in the orange where there is just air there." (girl, age 8) **Score = 2**

A score of 2.5 was assigned to a response that met all the criteria for bidimensional thought and some but not all of the criteria for integrated bidimensional thought. For example, to qualify for this score, justifications are based on a more in-depth understanding of properties of substances. This is demonstrated by the use of such terms as *molecules* or *particles* to explain the weight of substances indicating a fundamental understanding of particulate matter. However, such responses cannot be classified as truly integrated bidimensional thought as they fail to relate object density to that of water. In other words no compensation is made between object's weight and that of the medium.

Example: "The boat-shape foil has air particles in it and the foil is thinner and bigger so it's not all compact. The ball of foil will sink because the foil particles are compacted into one small ball so it's thicker." (boy, age 10) **Score = 2.5**

whereas

Example: "The boat-shape foil is lighter for the water because all the tinfoil is spread out (How will it help being more spread out?) Maybe the more expanded it is the thinner the tinfoil is. (What about the ball-shape foil?) The foil is thick because it's all bunched together and that might make it a little heavier because it's more solid, just like the coin was." (boy, age 10) **Score = 3**

Assigning a developmental score for each task level. The next step in the scoring system was to obtain a developmental score for each of the five task levels on all 60 protocols. This score was calculated by averaging the sum of the four item scores obtained at each task level. Finally, a Grand Mean for the complete task battery was calculated by averaging the sum of mean scores for each level. This provided an overall developmental score on the task battery for each participant. All sixty response protocols were scored "blind" to age and assigned to one of the five levels of structural complexity consistent with the age-level characteristics postulated by Case's neo-Piagetian theory.

Controlling for Language in Children's Justifications

The need to control for variability in children's language was critical if an objective scoring system was to be established to assess the various levels of understanding of buoyancy irrespective of children's age levels. Otherwise, language would have been considered an uncontrolled variable that could have conceivably influenced the scoring of age-level performance in this study. Not only would it have made the scoring of protocols more subjective in terms of favoring responses that were better articulated but it would have also posed a threat to the construct validity of the Buoyancy Measure itself. Instead, the results of the study might have reflected age-level language competence in scientific reasoning to a greater extent than they might have reflected age-level understandings of buoyancy. For example, age-level increases in conceptual understanding of buoyancy could be attributed to older children producing lengthier and more detailed explanations. Their command of knowledge is generally greater than their younger peers and thus provides them with greater opportunities to demonstrate their scientific knowledge. In some of the older children's explanations, the use of scientific vocabulary such as *molecules* and *particles* had to be carefully analyzed to determine whether children demonstrated an understanding of particulate matter when describing an object's substance. If children did not clearly explain what they meant by these terms even after further probing by the interviewer, a qualitative judgment was required to determine whether the response should be assigned a developmental score of 2 or 2.5 (refer to the scoring criteria for these levels of reasoning).

Fortunately, variability in the maturity of children's language was anticipated prior to establishing criteria for this measure. In a previous study investigating the nature and development of children's understanding of learning (Bickerton, 1994), I found it necessary to control for the varying levels of language maturity in children's definitions. Since both studies conducted interviews with children of different age levels and relied upon a scoring system that objectively analyzed children's responses to a set of questions, it was essential to incorporate into the scoring criteria a component that accounted for variations in language maturity.

Scoring criteria were generated in such a way as to prevent children from being penalized for using immature language. A student was permitted to obtain a score at any level with a "barebones" response (Griffin,1992) on condition that the "thought units" met the criteria for that particular level of reasoning. This was accomplished by paying minimal attention to the surface language structures in the response and merely focus on how many factors were considered and on whether they were related to each other. In other words, when scoring responses, the main focus of attention was to consider a child's overall reasoning about what determined buoyancy and to pay less attention to the quality of language used in each explanation. The language in children's explanations varied greatly not only across the three age groups but within age-levels.

A few item responses, particularly in the higher level tasks, (Task 4 & 5) proved challenging to score. Even with several prompts to clarify what was meant, the overall meaning of some explanations was not always obtained. Contradictory statements were sometimes included, resulting in inconclusive reasons for what determined buoyancy. These types of responses called for a qualitative judgment in terms of whether they could be considered as scientific explanations. If scientific factors were replaced by perceptual factors to justify a response, a developmental score of 0 was assigned to the explanation. This was often the case with Task 4 and 5 explanations. In a way this is understandable since the demands of these tasks may have overloaded children's working memory in terms of how much information needed to be considered simultaneously.

Scoring Criteria

The intent of this last part of the chapter is to provide the reader with a detailed conceptual analysis of how the scoring criteria were used to categorize children's buoyancy explanations into the five levels of thought. Numerous examples have been extracted from the protocols to illustrate how children's scientific reasoning can be articulated in terms of the hypothesized structural changes that are predicted to occur around the ages of 6, 8 and 10 years (Case, 1992)

Presentation of the scoring criteria and the categorization of protocol responses is organized into five sections that correspond to the five different task levels on the Buoyancy Measure. Within each task level, prototypical responses have been selected to illustrate the five hypothesized levels of understanding : predimensional, unidimensional, bidimensional, integrated bidimensional and vectorial (abstract) thought.

By organizing the data this way, a comparison can then be made of the different conceptual levels of understanding proffered by children in response to the set of four items for each specific buoyancy task. The justification responses have been carefully selected to demonstrate the many different conceptual representations offered by children at one level of understanding. That is, while the structural level of understanding remains the same, children's conceptual representations vary in their choice and coordination of factors.

Scoring Criteria for Developmental Levels of Understanding on the Buoyancy Measure

Response Levels for Task 1

Predimensional reasoning (level 0). Score = 0

Prototypical Response: It's heavy and all my soaps at home sink.

A score of 0 was assigned if a response conformed to the theoretical predictions of 4-year-old conceptions of buoyancy. Buoyancy predictions are based on one critical factor that determines an object's buoyancy, usually weight. Children articulate the weight of an object in global terms such as heavy or light. A few buoyancy predictions may be based on the size of an object in terms of whether it is small or large. At this level, there is no coordination between factors determining buoyancy which characterizes this form of reasoning as **predimensional**. Prototypical responses at this level might be characterized in this way : Objects float because they are light or small. Objects sink because they are heavy or big. In addition, children may justify their prediction further by including:

(1) worldly experiences e.g., "In my bathtub when I have a bath it {soap} always sinks." (girl, age 6)

or

(2) social or physical expectations of familiar objects e.g., " It's heavy and rocks sink." (boy, age 6)

Note: This additional information does not qualify as an example of dimensional thinking. Children are justifying their buoyancy judgments based on their worldly experiences or on their perceptual knowledge of the physical world. To qualify as dimensional reasoning, children need to coordinate the weight of an object with at least one other attribute (e.g., shape, size, hollow, solid) that relates to the object.

Dimensional Reasoning : To qualify as dimensional reasoning, children need to to justify their buoyancy judgments by coordinating the weight of an object with at least one other variable that affects an object's buoyancy (e.g., shape, size, material or texture).

Unidimensional reasoning (level 1). **Score = 1**

Prototypical Response: The ball is so light and has a round shape. (Weight + shape)

A score of 1 was assigned if a response conformed to the theoretical predictions of 6-year-old conceptions of buoyancy. Children consider two critical factors when considering an object's buoyancy; they need to coordinate the weight of an object with one other scientific factor that affects an object's buoyancy. In so doing, children demonstrate one dimensional structure in their reasoning. Most 6-year-olds select two variables from the following factors - weight, shape, material, texture/substance or size in varying paired combinations. The weight of an object continues to be articulated in global terms (i.e., heavy, light).

The following combinations represent unidimensional reasoning in **Task 1** and are listed in order of frequency :

• **weight coordinated with a shape attribute (e.g., boat-shaped, round, curved)**

Example: It's light and it has a round shape {plastic ball. (girl, age 6)

With most 6-year-olds, anything "round" or "circled" floats (e.g., "This fools gold is very heavy and there's nothing round that makes it float.") (boy, age 6)

• **weight is judged by texture of the object**

Examples: The cork feels light and soft. You can squeeze it. (boy, age 6)

The cork is light and feels foamy. (girl, age 8)

• weight is judged by object's material (substance)

Example: The cork is light because it's wood and wood floats. (girl, age 8)

Intermediate level. **Score = 1.5**

If a child refers to an object as " It's small and heavy for its size," a score of 1.5 was assigned. Although only two factors are coordinated in this response (weight and size), they are the two critical factors that determine an object's density and consequently its buoyancy. Therefore, this type of reasoning demonstrates a more sophisticated understanding of buoyancy and warrants a higher rating than those responses categorized as unidimensional.

If a child relates the weight of an object to the water, a score of 1.5 was assigned as an attempt to compensate between object and liquid was made.

Example: The soap is a little bit heavy for the water. (boy, age 6)

Bidimensional reasoning (level 2). **Score = 2**

Prototypical Response: The ball is very light because it's made out of plastic. It's got air in it. (How will air help?) air is a lot lighter than water. (Weight of ball is coordinated with [1] its material {i.e., plastic} and [2] the presence of air inside.)

A score of 2 was assigned if a response conformed to the theoretical predictions of 8-year-old conceptions of buoyancy. Children need to consider three critical factors when making a buoyancy judgment. For the most part, an object's weight continues to be considered as the most critical factor and is now related to two other attributes that may affect buoyancy (e.g., shape, texture, size, material and whether an object has air in it or not). These factors need to be compared and interrelated to each other in such a way as to represent two dimensional structures, that is, two sets of relationships between factors.

At this level children are beginning to focus their attention on substance properties which are described in terms of (1) texture (i.e., soft, hard), (2) material (i.e., wood, plastic) or (3) whether an object contains air or not (hollow vs. solid). Such properties are commonly related to an object's weight when making a buoyancy judgment. Children believe that if an object contains air it will float because air is lighter than water. I term this the "air theory."

Examples: The plastic is light and the ball is filled with air. (girl, age 8)

There's nothing in it {the ball} It's hollow and it feels light (Why?) Because there's air inside. (girl, age 8)

To qualify as a **level 2** response, two of the following combinations must be included in children's explanations:

- weight is judged on whether an object is hollow or solid
- weight judged by object's material (light or heavy)
- weight related to substance (description of texture)
- weight determined by whether an object contains air or not
- weight of object compared to weight of water
- weight judged in comparison to weight of previous objects (e.g., The cork is a lot lighter than this rock.)
- weight of object related to shape attributes
- weight related to size

Examples of bidimensional responses:

The ball is hollow and air is inside it. (How will air help?) It makes things light. (girl, age 8)

The rock is really heavy and it's solid. It's hard all the way through and it's heavier than the water. (boy, age 8)

The cork is made out of really light wood and has holes in it. (How do the holes help make it float?) They have air inside them. (girl, age 8)

The cork is not as heavy as the fool's gold. It's wood and doesn't have as much weight as the rock. (boy, age 8)

The soap is heavy because it's all packed together and doesn't have holes in it like the cork did to let in air. (boy, age 8)

EXCEPTION: A response may omit any reference to weight (although it appears to be inferred). Often in these cases substance properties become the critical factors in a child's reasoning. If three different attributes related to substance are coordinated in a response then it can be rated as bidimensional. If only two attributes are included then another factor such as shape or size must be included to qualify as bidimensional.

Examples: The ball is huge and not solid so it gets lots and lots of air pockets. Well maybe not air pockets just air. (boy, age 8)

The cork is almost like a tissue kind of thing (How?) It's kind of flexible and softer (comparing cork to the rock) You can press on it {the cork} and it will go in a little bit. (girl, age 8)

Intermediate level. **Score = 2.5**

When children determine an object's buoyancy based on a more in-depth understanding of particulate matter but fail to make a comparison between the weight of the object in relation to the weight of the medium (e.g., water) a score of **2.5** may be given. These responses transcend level 2 but fall short of reaching a level 3 response. Children demonstrate a more in-depth understanding of density by describing substance in terms of *molecules* or *particles*. However, such responses are not truly integrated responses because they fail to relate an object's density to that of the water. Children continue to relate two critical factors upon which they judge an object's weight but, in addition, demonstrate some understanding of an object's substance by including terms such as *molecules* or *particles*.

Examples: The rock is heavy because it's not hollow and is full of stuff inside. It's got no air molecules in it. (boy, age 10)

The ball is hollow and has lots of air molecules inside it. And it's made out of plastic. It's hard but very light. (girl, age 10)

The rock is heavy and has minerals in it. (What do you know about minerals?) They are little chunks of rock (Are they heavy or light?) They're light but when you put them together like this (holding up the rock) they turn heavy. (girl, age 10)

Integrated bidimensional reasoning (level 3). **Score = 3**

Prototypical Response: "The ball is lighter than the water because it's got air in the middle. (What about the plastic on the outside?) That's lighter than the water too. (Weight of ball is related to weight of the water ; weight of ball is judged on (1) hollow shape and (2) the presence of air).

A score of 3 was given if a response conformed to the theoretical predictions of 10-year-old conceptions of buoyancy. Like the previous level, two coordinated dimensional structures are present. That is, children continue to consider how two variables can affect an object's weight and determine its buoyancy. However, the relationship or coordination between variables has to be represented in a more integrated fashion than for Level 2. At this higher level, children need to demonstrate some form of compensation between object and medium. In other words, **a relationship must be made between the object's weight and the weight of the water** when making a buoyancy judgment. Compensation may be articulated through size and surface area or may be characterized as "tradeoffs" between the properties of the object and those of the medium. Any form of compensation requires the assembly of a higher-order relationship between variables. Hence, this pattern of thought is labeled **integrated bidimensional.**

Children now incorporate into their knowledge systems the notion of volume and begin to see how this dimension can inform buoyancy judgments. Whereas during the earlier levels the dimensions of size and volume may have been undifferentiated, children now demonstrate the ability to differentiate the two variables.

Example: The one foil that is shaped like the bottom of a boat will float because the air is in it. (Anything else?) The foil is spread out in this boat-shape one. (So how will that help make it float?) There's less weight on one point in the water. The ball of foil will sink because it's completely crushed together. (boy, age 10)

N.B. Response becomes more integrated with the concept of weight distribution and the different densities of the objects.

Compensation might be explained in terms of :

- **an object's substance or density and how it relates to the weight of the water**

Example: The ball is full of air and is sealed. It's made of plastic and plastic is lighter than water. (girl, age 10)

- **an object's weight distribution (surface area, size) and how it relates to the weight of the water.**

Example: The rock is small and heavy for its size so it's not lighter than the water.

An integrated response = weight of object + 2 other factors about the object (shape, substance, size) + a comparison of object's weight to medium (e.g., water)

<u>**Univectorial (substage 1 of the vectorial stage).**</u> **Score = 4**

Prototypical Response: If you weighed the same volume of water as that of the plastic ball the weight of the water would be heavier than the weight of the ball. (boy, age 12) (Density explained in terms of proportional reasoning: weight per unit of volume)

A score of 4 was assigned if a response conformed to the theoretical predictions of 12-year-old conceptions of buoyancy. To determine an object's buoyancy at this level, children's reasoning becomes more dynamic focusing on the integration of weight and volume of both object and water. Children demonstrate an understanding of relative density which requires children to make a comparison of object and liquid densities to determine an object's buoyancy. This is expressed in terms of proportional reasoning: weight per unit of volume. Children no longer focus on concrete dimensions separately but focus on the vector that results from two dimensions being in opposition to each other, that is, object and medium.

Example: The rock is heavier than water. If there was a chunk of water as big as this rock exactly, it would weigh less than the rock. (What do you mean?) The same amount of water would weigh less than the same amount of rock. (boy, age 10)

Response Levels for Task 2

In **Task 2,** the weight of paired objects are held constant while shape, size and density are varied.

Predimensional reasoning (level 0). **Score = 0**

1. A weight comparison is made between paired objects with no explanation why: The bowl feels lighter than the potato (Why, when they are both the same weight?) I don't know. (girl, age 6)

Unidimensional reasoning (level 1). **Score = 1**

Prototypical Response: This foil is sort of light and is sort of like a bowl or canoe. (weight + shape) (boy, age 6)

Two factors are combined to make a decision regarding which object floats. Usually buoyancy judgments are based on shape attributes (e.g., boat-shaped, round bottom, a hole in the middle, has sides). Since weight is held constant in this set of tasks, children may not articulate whether an object seems light or heavy. Instead children may base their buoyancy judgments on two shape attributes. When comparing the two objects, children at this level demonstrate some understanding that bowl-shaped objects float while solid objects sink. Possible unidimensional responses:

- **Weight is coordinated with a shape attribute**

Example: The metal hat is light and the bottom is round. (girl, age 6)

or

- **Weight is coordinated with substance**

Example: The potato is sort of heavy (Why?) Because of its insides. The part that you eat is sort of heavy.(boy, age 6)

or

• **Coordination of <u>two</u> shape attributes**

Example: It's sort of shaped like a boat. The edges hold it up and it has a hole in the middle. (boy, age 6)

In Task 2.4 : the two wooden solids might take on shape attributes such as logs (cylinder) or boats (pyramid) : This is like a boat bow (pointing to the tip of the pyramid) and this one is like a log and logs float. (girl, age 6)

or

• **Coordination of <u>two</u> different factors** (e.g., substance and size)

Example : The potato is fat and full of stuff. (boy, age 6)

They're both made of wood and have a flat bottom. (material + shape) (girl, age 6)

<u>Intermediate level.</u> **Score =1.5**

<u>Three</u> factors are considered to affect an object's buoyancy but only <u>two</u> of these factors are coordinated. Children are aware that the bowl-shaped object will float because there is air inside the hole. Although air is mentioned, the response does not qualify as Level 2 thought if the "air theory" is not explained. That is, if children do not explain that air is lighter than water then the response falls short of bidimensional reasoning.

Example: The bowl is round and there's a hole in the middle (What's in the hole ?) There's air in there. (How does that help?) I don't know. (boy, age 6)

<u>Bidimensional reasoning (level 2).</u> **Score = 2**

Prototypical Response: This foil has air in it and this one doesn't so the air will hold it up.

(How?) It's got sides on it. (Weight is related to (1) air and (2) shape) (girl, age 8)

Buoyancy predictions are based on the coordination of three critical factors. Since weight is held constant in this set of tasks, children may not articulate whether an object seems light or heavy. Instead children consider shape attributes but unlike the previous level more attention is directed towards whether an object has a hole in the middle or not. In Level 2 responses, the terms **hollow** or **solid** are often articulated to differentiate this shape attribute. This is then coordinated with a second factor, which I have interpreted as the "air theory." A common theory maintained by eight-year-olds is that if an object's shape can contain air it will float because air is lighter than water.

Bidimensional responses may be represented by the following coordinations:

- **weight is judged by shape of object + "Air Theory"**

Example: The bowl is shaped like an oval. It's curved on the bottom and has air inside of it. (girl, age 8) **or**

- **weight related to whether object is hollow or solid + "Air theory"**

Example: "The bowl will float because there's nothing inside it. It's hollow so the air will push it up. And in here, there's all potato stuff and that will push it down because it's all solid and no air can get in it." (boy, age 8)

Example: "This shape (bowl-shaped foil) is hollow in the middle and air can get inside it. And the small foil is all crumpled together. It made all the air come out." (girl, age 8)

or

- **weight is judged by substance + "Air Theory"** (usually in Task 2.4 responses)

Task 2.4: Two wooden solids. A common response makes reference to wood to judge whether the solids will float or not. Children usually make the connection that wood floats.

To qualify as bidimensional reasoning, children must consider any two of the following relationships:

weight of solids related to wood substance

weight related to shape attributes relating to logs (cylinder) or boats (pyramid)

weight of wood substance compared to weight of water

wood substance determined by presence of air inside

weight related to size of solids

Example: Wood has little air pockets so it can hold air. So it can be lighter than the water. (girl, age 10)

Intermediate level. **Score = 2.5**

Similar to Task 1, some responses may examine in detail the density of the substances (e.g., potato, the two different metals, tin-foil , wood solids) and how it affects an object's weight distribution. Such responses consider size, shape and particulate matter of substance. Although this is evidence of children compensating for the different factors that affect an object's buoyancy, it does not qualify as a true level 3 integrated bidimensional response as no reference is directly made to how the object's density relates to the density of the water. With such responses, **a score of 2.5** was assigned.

Example: Although the metal hat and coin are the same weight, the metal hat's volume is larger than the coin's so it has less weight in one area than the coin has. (boy, age 10)

If no reference is directly made to how the object's density relates to the density of the water a score of 2.5 is given.

A score of 2.5 was also assigned to explanations that include the terms *molecules* or *particles* when describing an object's substance. This suggests a more in-depth understanding of particulate matter and the concept of density. Compare these two examples:

Example 1: The boat-shape foil has air particles in it and the foil is thinner and bigger so it's not all compact. The ball of foil will sink because the foil particles are compacted into one small ball so it's thicker. (girl, age 10) **Score = 2.5**

whereas

Example 2: The boat-shape foil is lighter for the water because all the tinfoil is spread out (How will it help being more spread out?) Maybe the more expanded it is the thinner the tinfoil is. (What about the ball-shape foil?) The foil is thick because it's all bunched together and that might make it a little heavier because it's more solid, just like the coin was. (boy, age 10) **Score = 3**

Integrated bidimensional reasoning (level 3). **Score = 3**

Prototypical Response: The one foil that is shaped like the bottom of a boat will float because the air is in it. (Anything else?) The foil is spread out in this boat-shape one. (So how will that help make it float?) There's less weight on one point in the water. The ball of foil will sink because it's completely crushed together. (boy, age 10)

N.B. Responses become more integrated with the concept of weight distribution and the different densities of the objects)

Integrated responses examine in more detail the density of the substances (e.g., potato, metal, tin-foil , wood solids) and explain how this affects an object's weight distribution on the water. Children continue to judge an object's weight based on two other factors. For example, shape attributes, often expressed by the terms **hollow** and **solid** are frequently used in conjunction with the "air theory." To qualify as an integrated response, children must also show some form of compensation between the object and water. In other words, they must differentiate the properties of the object and the water when considering an object's buoyancy.

Examples: The metal hat has air in it and the coin has not much air and is a flatter shape. (What else will make the hat float?) The shape of it. (How?) The curve part will help it sit on the water and the air will also stay in it. (boy, age 8)

The boat-shaped foil is probably lighter for the water because the tin foil is all spread out. (How will that help?) Maybe the more expanded it is the thinner the tinfoil is so it's lighter for the water. (boy, age 10)

In Task 2.4, compensation must be demonstrated by children judging the properties of wood as a substance in terms of its density (e.g., "this is light wood not heavy stuff."), then the shapes of the solids should be explained in terms of weight distribution or surface area which in turn is compared to the weight/force of the water.

Example: They're made of light wood and have flat sides so they can sit on the water nicely. If you put them in straight up and down they'll sink first. (Why?) Because that is the heavy end (points to the tip of the pyramid and end of the cylinder). They need space to spread out on the water. Maybe they will just go down on their heavier ends and then pop up and just sit on the water on their flat sides. (boy, age 10)

Univectorial reasoning (level 4). **Score = 4**

A direct relationship of the object's density to the density of the water is articulated. In other words, children understand that buoyancy depends on the relative density between object and medium. This may be expressed in terms of proportional reasoning: weights of equal volume of substance and water are compared to determine buoyancy. Alternately, a response may articulate the downward force of an object's weight in relation to the upward force of the water's weight.

Example: The hat is made of aluminum and which is a lighter metal than the coin which is brass. (But they're the same weight) Yes but the metal hat's volume is larger than the coin's so it has less weight in one area than the coin has. (So why will it float?) If you had the same volume of water as you would the hat then the water would be heavier so the hat would float. (boy, age 12)

Response Levels for Task 3

In **Task 3,** the weight of the first two paired objects is held constant. In addition, the objects' shape and size are held fairly constant. In the last two paired items shape is held constant while weight, size and substance vary. My aim is for children to test the effects of an object's substance.

Predimensional reasoning (level 0). **Score = 0**

Perceptual factors tend to govern reasoning when tasks become more difficult. In this set of tasks, weight may be judged by a superficial attribute strictly for the purpose of searching for holes in the object that might let in water.

Examples: The parsnip is bumpy so it will let in water. (girl, age 6)

The carrot has lines on it and the parsnip doesn't. (boy, age 8)

The orange has tiny holes in it so it will breathe in water. (girl, age 8)

Alternately, if children simply compare the weight of the paired objects (even though weight is held constant for the first two tasks) without explaining why the object seems lighter a **score of 0** is also assigned. Children are only considering one factor.

Unidimensional reasoning(level 1). **Score = 1**

Prototypical Response: The orange seems lighter than the beet. (Why?) Because it feels softer and the beet feels a little hard. (Weight is related to substance/texture) (girl, age 6) Children tend to judge weight by comparing substance in terms of the texture.

- **weight based on the comparison of each substances' texture or amount**

Example: The orange will float because it's not quite that heavy and the beet feels heavier. (Why?) It has more stuff inside than this orange. (boy, age 6)

Since weight is held constant in the first two tasks, children may not mention weight in their explanation. However, it is intuitively considered in their reasoning. Consider these two examples: The parsnip will float because it's shorter than the carrot. (girl, age 6)

The orange will float because it's squishier and the beet feels harder. (boy, age 6)

With these two responses weight is inferred.

Task 3.1 (carrot vs parsnip) Symmetry of shape may play a factor in children's reasoning when comparing the size of the two vegetables. Children think the parsnip will sink because " it's too fat up here." (The parsnip is not as uniform in shape as the carrot)

Example: The parsnip will sink because it's fatter at one end. (an incorrect prediction) (girl, age 8)

This part of the carrot is small and round and this part of the parsnip is bigger. (boy, age 6)

The parsnip will float because it has a big round part and the carrot has a smaller round part. (boy, age 6)

Intermediate level. **Score 1.5**

When weight is based on a comparison of size a score of 1.5 is given even though only two factors are articulated. This is a more ***integrated response*** than Level 1 thought simply because size and weight are the essential factors to consider when determining an object's buoyancy. Therefore, this type of reasoning demonstrates a more developed understanding of buoyancy and warrants a higher rating than those responses categorized as unidimensional.

Example : The parsnip is light for its size and the carrot is heavy for its size. (girl, age 8)

Example from Task 3.3 (sugar cube vs. wood block)

> "This wood is floating kind of wood because it's light. (So why will the sugar-cube sink?) It's heavy for its size and yet feels light. (What about the block?) It's light for its size so it will float." (boy, age 8)

A 1.5 score is also assigned to responses that directly compare the weight of the two substances.

Example: The stuff inside the parsnip feels lighter than the stuff inside the carrot. (girl, age 8)

Once again only two factors are articulated, weight and substance. However, this type of response is characterized as more advanced than unidimensional thought due to weight being directly related to an object's substance.

Bidimensional reasoning (level 2). **Score = 2**

Prototypical Response: The orange will float because it feels softer and looks a bit bigger than the beet. (When you said softer what does that tell you about the orange?) It's got lighter stuff inside. (Weight is related to substance and size.)

Buoyancy predictions are based on the coordination of three critical factors. Two different factors (e.g., size, substance) are related to an object's **weight** to determine its buoyancy. At this level, children generally compare the feel or texture of the substances to determine which of the two objects might float. That is, if the texture is soft and squishy, children consider the substance as light stuff; if the texture is hard or hard-packed the substance is considered as heavy stuff. To become a **bidimensional response,** children also include in their justifications that soft, squishy substances contain air inside and are lighter whereas hard substances have no room for air and are heavier.

- **weight is related to texture/substance + "air theory"**

Example: The beet will sink because it feels hard and has no air inside it. And the orange will float because it has little pockets of juice and air inside it. There's some squishy parts in the orange where there is just air there. (girl, age 8)

Example: The parsnip will float because the stuff inside is almost like a sponge as it gets all the air in it. (girl, age 10)

An alternative form of bidimensional reasoning:

- **object's weight related to a comparison of size + substance**

Example: The parsnip will float because it's smaller than the carrot (But it looks fatter to me!) Yes, but at one end it's skinnier and not as long as the carrot. (What else?) The parsnip feels softer so it could be lighter. The carrot feels harder and heavier. (boy, age 8)

In Task 3.3, to qualify as bidimensional, children must compare the substances wood and sugar when making a buoyancy judgment and then coordinate this with another factor to determine buoyancy judgment (e.g., size, weight of water). Often children mention that there are tiny holes in the sugar-cube that let in water that will take it down. This reasoning can be related to the "air theory" dimension where water is heavier than air.

In summary, level 2 thinking is represented by the coordination of any two of the following dimensions:

• weight is assessed by a comparison of each object's texture/substance (soft infers light material; hard infers heavy material)

• weight is also determined by the presence or absence of air in object's substance

• weight is judged on a comparison of **size** of paired objects

• distribution of object's weight / concern for symmetry of shape (Task 3.1 - parsnip)

• weight of object's substance is compared to the weight of the water

Intermediate level. **Score = 2.5**

Similar to Tasks 1 and 2, some responses may examine in more detail the density of the substances (e.g., carrot, parsnip, orange, beet, sugar, wood). In these responses size and substance are more closely related in terms of how they affect an object's weight distribution. Children's justifications show evidence of compensatory strategies by pitting substance and size against each other to determine an object's weight distribution on the water. Unlike the previous transitional responses, children do not appear to use the terms *molecules* or *particles* as much to describe an object's substance. Instead they begin to compensate an object's substance and size in a more related or integrated manner.

Example: The parsnip is spongier material and looks like more air can go through it. (So how will that make it float?) It's broader than the carrot and it looks like it spreads out the weight more so it will float. (Why will the carrot sink?) It's skinnier and feels heavier because the material it's made of doesn't let any air in there. (girl, age 10)

Although children are beginning to compensate for different factors that affect an object's buoyancy, their responses do not qualify as true level 3 integrated bidimensional responses as **no reference is directly made to how the object's density relates to the density of the water.** With such responses, **a score of 2.5** was assigned.

Integrated bidimensional reasoning (level 3). **Score = 3**

Prototypical Response: The beet has real hard stuff in it and it's smaller than the orange so is more compact. I think it will make a bit too hard a force when it goes in so the water will probably push it down. (Weight related to substance and size and then beet's weight is compared to the water.)

An integrated bidimensional response must include the following when making buoyancy judgments: (1) two factors are used to judge an object's weight and (2) a comparison of object's weight to that of the water is made. An integrated response manifests the recognition of a closer relationship between the properties of the object and water. In other words, children begin to demonstrate compensation by differentiating between the properties of object and medium (water). For example, compensation may be addressed in terms of weight distribution (as evidenced by the integration of object's size and weight) and how it relates to the weight/density of the water. The understanding of water displacement or downward force of object on the water is evident.

Example: The parsnip is broader {than the carrot} and it looks like it spreads out the weight more so it will float better on the water. (girl, age 10)

Example: The parsnip will float because it has a bigger end here and won't let in any water and it is light. It's fatter than the carrot so will sit on the water better when it breaks the surface tension and push its way into the water. (This suggests that he understands the concept of water displacement for objects to float). This carrot will break the surface tension and sink because it's sharper. (What do you mean?) It's thinner than the parsnip. (boy, age 10)

Example: The block is made out of a lighter wood. And the sugar cube is smaller and doesn't interrupt the water tension so much ...the surface of the water (What do you mean?) When bigger things get stuck in and if they're too light the water can't close over them. If they're small enough the water tension is strong enough to close over top of them and bring it down. (After testing: Why did the sugar-cube sink?) It's so small and the water tension can close over it. (boy, age 10)

Example from Task 3.3 (sugar cube vs. wood block)

The block will float because the water is heavier than the wood. (Why?) This wood is floating kind of wood because it's light and has air in it. (girl, age 10)

Univectorial reasoning (level 4). **Score = 4**

Prototypical Response: The sugar cube will sink because it's heavier stuff than the wood. For the size of the cube the same amount of water is lighter than the cube. (boy, age 12)

The density of an object's substance is related to the density of the water (i.e., relative density). This may be expressed in terms of proportional reasoning: weights of equal volumes of substance and liquid are compared to determine buoyancy. Alternately, a response may articulate the downward force of an object's weight in relation to the upward force of the water.

<u>Response Levels for Task 4</u> (Testing an object's buoyancy in <u>two</u> different liquids)

<u>Predimensional reasoning (level 0).</u> **Score = 0**

These tasks appear to overload working memory capacity of 6- and 8-year-olds in that there are too many factors to simultaneously manipulate when making buoyancy judgments. To compensate for this, perceptual factors tend to govern reasoning when the tasks become more difficult. Children intuitively know that when salt is added to water it makes things float. But since the tasks have become more complex, children may justify their predictions using 'visible' perceptual properties of the salt to explain unknown 'invisible' physical factors that determine why objects float on salt water. A common explanation often given by 6-year-olds for why objects will float in salt water is: "The salt pushes it up." Although this explanation does suggest that children intuitively know that salt water is heavier than ordinary water it does not qualify as dimensional reasoning as **no** reference has been made regarding the actual weight of salt water in comparison to the ordinary water. At this level, the weight or force of the liquid is determined by the presence or absence of salt in the water.

The following are other examples of children's perceptual justifications for their buoyancy predictions:

> The salt spins around the egg. The salt will gather underneath the egg and push it up. (girl, age 6)
>
> The salt water has a better taste to it. (girl, age 6)
>
> The rosewood will float in the salt water because it's white..all the salt is spinning around. (boy, age 6)
>
> The rosewood has paint on it and it's smooth and it has a smell on it. (boy, age 6)

<u>Unidimensional reasoning</u> (level 1). **Score = 1**

Prototypical Responses: The salt water is heavier than the ordinary water and so it will push the egg up better. (boy. age 8)

Children compare the weight of salt water to ordinary water when deciding where the object will float. That is:

• **Weight (substance) of water is compared to weight (substance) of salt water.** This is coordinated with the notion that salt has been added to the water and so has a greater force to hold up object.

Example: (Why did you choose salt water?) Because the salt water is heavier than the ordinary water. There is salt in it. There's more stuff in it than the ordinary water. (girl, age 8) Buoyancy is judged by the weight of the object in relation to the heavier liquid.

Example: It looks like it's salty in there. (How will that help?) Maybe it's going to make the egg float because there's more salt in there. (boy, age 6)

Example: Because this water has salt in it and this one doesn't have anything in it. (How does that make a difference?) This has salt and has more weight so it can push more up. (boy, age 8)

or

• **weight of object is compared to the weight of <u>one</u> liquid**

Example: The grape is light enough for the plain water to carry it. (incorrect prediction) (girl, age 6)

Example: The salt water seems to push things up...and the lime is pretty heavy. And the salt water can lift up heavy things I guess. (What about the ordinary water?) It pulls things down (Why?) Because they're too heavy. (boy, age 6)

• **weight of object is related to substance**

Examples: The grape is light and squishy. (Incorrect prediction for why it will float in water) (boy, age 6)

The lime is hard and heavy. (Reason given for why it will float in salt water) (boy, age 8)

• **weight of object related to shape or size**

Example: Because the egg is round ... and this is clear water and something that is round floated in the big water. (Referring to Task 3.4 -tennis ball) (girl, age 6)

Intermediate level. **Score 1.5**

An intermediate score was assigned to responses that examine the object's weight in terms of substance, usually mentioning the presence of air inside but failing to articulate why this will help the object's buoyancy.

Example: The grape has air in it and it's built up with all the juices. (boy, age 8)

(An explanation for why the grape will float in ordinary water)

Although the reasoning is incorrect, its underlying dimensional structure demonstrates a transitional response between Level 1 and Level 2 understanding.

Alternatively, a score of 1.5 was awarded to responses that compare the object's weight to the two liquids but fail to demonstrate an understanding that the object is light for one liquid and heavy for the other.

Example: The grape is lighter than the water. (What do you mean?) The grape is light for ordinary water. (What about the salt water?) I'm not sure. (girl, age 8)

<u>Bidimensional reasoning (level 2).</u> **Score = 2**

Prototypical Response: This lime is going to sink in ordinary water because it's a lot heavier than that water. And the lime will float in the salt water because it's light for that water.

To qualify for a score at this level, (1) the weight of the object must be compared to the weight of <u>both</u> liquids or alternatively (2) the object's weight may be related to <u>one</u> other factor (e.g., size, substance or shape) related to the object to form one dimension and then coordinated to the weight of <u>one</u> of the liquids to form a second dimension.

In Task 4, level 2 reasoning may be represented in the following ways:

- **Weight of object compared to the weight of <u>two</u> liquids.**

Example: The grape is not too heavy for the salt water but is too heavy for the ordinary water. (boy, age 10)

Example: (Why will the rosewood float in salt water?) Because the salt will hold it up and make the rosewood lighter than when it is in the ordinary water. The rosewood is light for the salt water and is very heavy for the ordinary water. (boy, age 8)

Example: (Why will the lime float in salt water?) Ordinary water can't hold heavy things and the salt water can. We should pour the salt water into the ordinary {water}bowl and then the lime might float! (girl, age 10)

Example : The salt makes the water heavier than the ordinary water and that makes the egg seem lighter on the salt water. (boy, age 8)

Example: The salt water is heavier than the regular water and so is this lime pretty heavy. So the lime will need the heavier water to hold it up. (girl, age 10)

- **Weight of object judged by its substance and then compared to weight of one liquid**

Example: The grape is full of juice and it's a little heavy for the ordinary water. (girl, age 10)

• **Weight of object judged by its shape and then compared to weight of one liquid**

Example: Because of its shape ....It's (lime) like the egg. But even though the egg didn't float in ordinary water I think the lime will float in ordinary water. (girl, age 8) An incorrect judgment.

Example : Because the grape is lighter than the plain water and the grape is rounder than the egg. (girl, age 8) An incorrect judgment.

Intermediate score. **Score = 2.5**

A response was awarded a score of 2.5 if a more in-depth comparison was made between the liquid densities in terms of the salt water having more molecules in it than ordinary water.

Example: The egg will sink in the fresh water because it doesn't have the type of particles it will take to make it float. The salt particles in the salt water will make the water heavier and push up on the egg. (boy, age 10)

Integrated bidimensional reasoning (level 3). **Score = 3**

Prototypical Response: The salt water is a thicker substance than the ordinary water and it's harder for the egg to go down to the bottom. (What do you mean?) The egg is sort of heavy inside and salt water is stronger. (girl, age 10)

As can be seen from the above example, substance properties of both object and liquids are taken into consideration and used to compensate between object and medium. The object's density is related to the density of the two liquids. For instance, reference is made to the thickness or particulate matter of the liquids and then related to the object's weight in terms of its substance.

Example: The salt water is heavier so it's thicker. (Do you mean denser?) Yes that's it. (So why will the denser liquid hold up the grape?) It will hold the grape because it's denser, more solid than the ordinary water. (But isn't the grape light?) Yes, but the grape doesn't have any air in it. It's a bit squishy so has more liquid stuff in it. (girl, age 10)

Example: The grape is mostly made out of water so it's fairly heavy inside. (So why will the grape float on salt water?) Well it's heavier than the fresh water. (I think you are referring to the density of the grape) Yes, the density of the grape is heavier than fresh water but not salt water. (boy, age 10)

Example: The lime is a bit more air-filled. And the salt water is still a thicker and heavier substance than the insides of the lime. (girl, age 10)

Example: The salt water is thicker and it's got more surface tension like it can hold heavy things. (like the egg?) Yes. (What do you mean by thicker?) I mean salt water is heavier. Salt water is not as liquidy as the normal water. (What do you mean?) The salt is tied in between the water molecules. (Are you saying there's more molecules in the salt water?) Yes, because in normal water there are spaces between the molecules really teeny ones and in salt water the salt molecules are taking up the spaces so the water is more compressed. (boy, age 10)

<u>Univectorial reasoning (level 4).</u> **Score = 4**

An understanding of relative density between object and liquid is demonstrated. An object's weight is compared to the weight of an equal volume of water and an equal volume of salt water.

Example: The salt water is heavier than the fresh water. (How will that help?) That will make it heavier than the egg's volume.... the same amount of salt water that is. So this egg will be lighter than the same volume of salt water so it will float. (boy, age 12)

Example: The same amount of volume of salt water would be heavier than the lime so it will float on salt water. But the same amount of volume of fresh water would be less than the lime so the lime will sink. (boy, age 12)

Response Levels for Task 5 (Testing two object's buoyancy in two different liquids)

Predimensional reasoning (level 0). **Score = 0**

1. Children coordinate non-scientific factors related to the object or liquids.

Examples: The duck will stick on the molasses because the molasses is gooey. (boy, age 6)

The oil is wet and the cranberry is dry. (girl, age 6)

Lots of ducks swim on salt water. (boy, age 6)

Ducks float in any kind of water. The duck got trapped in the molasses because it's thick and oily. (boy, age 6)

The kiwi floated in the salt water because it was sweet and the salt was attracted to it. (girl, age 8)

2. When only a comparison of weight (shape, size or substance) is made between the two objects then it is considered predimensional.

Example: The cranberry is lighter than the blueberry.

This is a predimensional response since the only critical factor considered is weight.

Unidimensional reasoning (level 1). **Score = 1**

1. When deciding which of the paired objects float on both liquids:

- **weight of one object is related to one factor (substance, texture, size, shape).**

Usually, a comparison of the two objects is made based on this one factor.

Examples: The kiwi is rounder; The kiwi is softer than the duck; The blueberry is littler than the cranberry.

2. When deciding where the other object floats or sinks:

- **Object's weight is related to its substance (texture, size, shape) to determine which liquid it will float in.**

Example: The blueberry is squishy (age, 6) (justifying why it will float on salt water)

Intermediate level. **Score =1.5**

If a response compares the weight of one object to the weight of one liquid then a score of 1.5 was assigned.

Example: The blueberry is light for the salt water. (boy, age 8)

If the presence of air was mentioned in either object or liquid without an explanation for the "air theory," a score of 1.5 was also given.

Example: The blueberry will float in salt water because the salt water has air in it and will make it float. (girl, age 8)

Bidimensional reasoning (level 2). **Score = 2**

1. When deciding which of the paired objects float on both liquids:

- **Weight of object is based on two of the following factors (1) substance (2)**

hollow or solid (3) shape (4) size or (5) the presence or absence of air (Similar responses to Task 1, 2 & 3).

Example: I think the kiwi has air inside it and it feels kind of soft. (boy, age 10)

Example : (Why will the cranberry float on both?) The blueberry is wrinkled and all mushy so it must have more molecules in it than the cranberry. (girl, age 10)

• **Weight of object is judged on one of these factors (1) substance or (2) whether it's hollow or solid or (3) if it contains air (4) shape (5) size and then coordinated to the weight (or substance) of each liquid.**

Example: The kiwi fruit has air pockets so is light and will float on the salt water. The molasses is very thick so will probably hold it up too. (boy, age 8)

Example: The kiwi will float on the molasses because it's a thicker and heavier liquid. And it will sink in the salt water because of the kiwi's heavy insides. (boy, age 10) An incorrect prediction.

• Weight of object is compared to both liquids.

Example: The duck feels light and is light for the salt water and the molasses. (girl, age 8)

Example: The cranberry is very light and is not too heavy for both of them (liquids). (girl, age 8)

Intermediate score. **Score = 2.5**

A response is awarded a score of 2.5 if a more in-depth comparison is made between the liquid densities in terms of the salt water having more molecules in it than ordinary water.

Integrated bidimensional reasoning (level 3). **Score = 3**

To obtain this score, a response must include (1) a comparison of object substances, (2) a comparison of liquid densities and (3) a relationship demonstrating compensation for the two objects and two liquids.

Example: (Where will the blueberry float and sink?) The blueberry will sink in the oil because the oil isn't as dense{as the salt water} and oil will let almost anything sink. (Why did you choose salt water?) Because it's more dense and there's more juice and stuff in the blueberry {than the cranberry}. (boy, age 10)

Example: (Which berry will float on both?) The cranberry is heavier than the blueberry and there's more pressure inside it that will make it want to stay up more. And both liquids are really thick and they're thick enough to keep the cranberry up. The blueberry will float in the salt water because it's a heavier substance than the oil. The blueberry will sink in the oil because the insides of the blueberry are probably heavier than the cranberry's. And the oil doesn't have enough weight to keep it up. (boy, age 12)

<u>Univectorial reasoning</u> (Level 4). **Score = 4**

The concept of relative density is better articulated. That is, children compare the density of both objects and liquids by pitting the objects' weight, density and volume against the density of equal volumes of both liquids. Children demonstrate an understanding of proportional reasoning and provide a qualitative explanation of the density formula.

Example: The cranberry will float on both because its density is lighter than the same volume of oil or salt water. (boy, age 12)

Example: The blueberry will float on the salt water and not the oil because the salt water is heavier than the oil. And the heavier the liquid the better something floats on it. (**N.B.** Level 3 reasoning) (So why did you choose the cranberry to float on both?)

Because when I felt the weight of both berries they were almost equal but the blueberry is a lot smaller than the cranberry so the volume is smaller so the weight is packed into a smaller volume. (boy, age 12)

Interrater Reliability Results

A second rater, unfamiliar with the aims of the study, scored 24 out of the 60 protocols to confirm reliability of the scoring. Eight protocols from each of the three age-groups were randomly selected and were scored independently by the second rater to determine the reliability of the author's scoring of children's responses on the Buoyancy Measure. Since the test required qualitative judgment, scoring was done blind to age. It was important to rate the level of understanding of buoyancy that was reflected in each response according to the developmental criteria it met.

The rater was given a copy of the Buoyancy Task Battery which provided a brief description of the five buoyancy problems and the level of dimensional reasoning required to pass each task (see Appendix E). The training session began with a "walk-through" of the set of five tasks to familiarize the rater with the battery of buoyancy problems. This was followed by an explanation of the scoring criteria for each developmental level. Examples of prototypical responses for each developmental level were shared and discussed. Two examples were done by the rater independently and checked by me. Sufficient practice was given until the rater felt comfortable and competent to score task responses independently. To facilitate the scoring of protocols, a one-page condensed version of the scoring criteria (see Appendix F) and a list of the buoyancy factors (see Appendix G) children used in their explanations were given to the second rater to help simplify the rating of responses. At the end of the training session, the following suggestions were given to the independent scorer regarding her scoring procedure.

SUGGESTIONS FOR SCORING THE PROTOCOLS

1. Focus on scoring one task at a time. This makes it easier to match the criteria for the different levels of reasoning on that particular task.

2. Give an appropriate developmental level for a child's explanation even if it's an incorrect prediction and is not scientifically correct. This score reflects the child's structural level of reasoning , that is, the number of factors they use to determine an object's buoyancy. A second score is assigned to each question, specifically a performance score. The criterion for a performance score of 1 is a correct prediction + an appropriate explanation that corresponds to the required level of reasoning for that task.

3. Do not take into consideration explanations that are given after children have tested their predictions. Omit a score for responses that follow (**After Testing**). They are often higher than the first explanations.

The overall percentage of interrater agreement was 91%. Discrepancies between the two raters were never more than one level, the majority being only half a level apart. Assigning intermediate level scores of 1.5 or 2.5 generally relied on judgment calls and these scores were the ones that caused most of the inconsistencies between the two raters. However, all disagreements were resolved by discussion. The interrater agreements for each of the five buoyancy tasks were 93% , 88% , 84% , 95% , and 93% respectively.

Statistical analyses of the children's scores are presented in the next chapter.

CHAPTER 5 : STATISTICAL RESULTS

The purpose of a statistical analysis of children's performance on the Buoyancy Measure was to determine if there was empirical support for the hypothesized developmental sequence in children's conceptual understanding of buoyancy across the ages of 6, 8, and 10 years. The multilevel buoyancy tasks were designed to measure the following different levels of reasoning : Task 1 (predimensional), Task 2 (unidimensional), Task 3 (bidimensional), Task 4 (integrated bidimensional) and Task 5 (univectorial [i.e., abstract]). Furthermore, these tasks were ordered sequentially to determine if these levels of understanding were acquired in the order and at the ages that the theory proposed. The main goal of the study was to confirm the prediction that children's understanding changes systematically with age in a progressive manner consistent with the age-level postulates of Case's (1992) model of cognitive development in middle childhood. To confirm this hypothesis, the results of a statistical analysis on the data should reveal significant age-related differences in level of understanding of buoyancy at the ages of 6, 8, and 10 years.

Quantitative analyses were conducted on two sets of scores assigned to each protocol: (1) an overall performance score representing the number of tasks successfully passed on the measure with the criterion set at passing 3 out of the 4 problems within each task level and (2) a grand mean developmental score representing the overall level of reasoning on all 20 task items. To obtain a grand mean developmental score, a score was first assigned to each of the 20 task items. These item scores were then used to calculate a mean developmental score for each of the five buoyancy tasks by averaging the scores of the four item responses at each task level. Finally, a **Grand Mean** for the complete task battery was obtained by averaging the sum of mean scores for each level. This provided an overall developmental score on the task battery for each participant. These developmental scores were based entirely on each justification response supporting a buoyancy prediction and reflected a child's understanding of buoyancy at the hypothesized levels 0 - 4. The five developmental levels that had been established for the measure were as follows :

At Level 0 (*predimensional*), children were expected to predict an object's buoyancy based on its weight in global terms of heavy or light and not connect weight to another factor.

At Level 1 (*unidimensional*), children were expected to coordinate weight with another factor that integrates their understanding that an object's buoyancy does not rely entirely on weight alone.

At Level 2 (*bidimensional*), children were expected to consider simultaneously how several factors, particularly substance properties and size, affect an object's buoyancy. Children begin to differentiate an object's mass from its density and demonstrate an understanding that an object's substance is a more important factor to consider when determining buoyancy.

At Level 3 (*integrated bidimensional*), children were expected to extend their understanding of buoyancy to the medium as well as the object. They demonstrated an understanding that the two variables, object and medium, "trade off" or "compensate" for each other's density by comparing object and liquid substances.

At Level 4 (*univectorial*), children were expected to demonstrate an understanding of relative density using proportional reasoning regarding object and medium densities, that is, density = mass per unit of volume.

Analyses of Children's Performance Scores on the Buoyancy Measure

Descriptive Statistics

My first statistical analysis was to obtain an overall total performance score mean and standard deviation for each age group. Observed means (standard deviations) for 6-, 8-, and 10-year-olds were 1.95 (.39); 2.75 (.44) and 3.15 (.67), respectively. In **Figure 1**, the total performance scores are represented graphically and are compared with the predicted performance scores for each age group. Predicted scores established for 6-, 8-, and 10-year-olds were 2, 3, and 4, respectively, which represent the number of tasks each age group were expected to pass according to Case's (1992) theoretical predictions regarding the dimensional level of reasoning children are capable of demonstrating at the ages of 6, 8, and 10 years (i.e., unidimensional, bidimensional and integrated bidimensional, respectively).

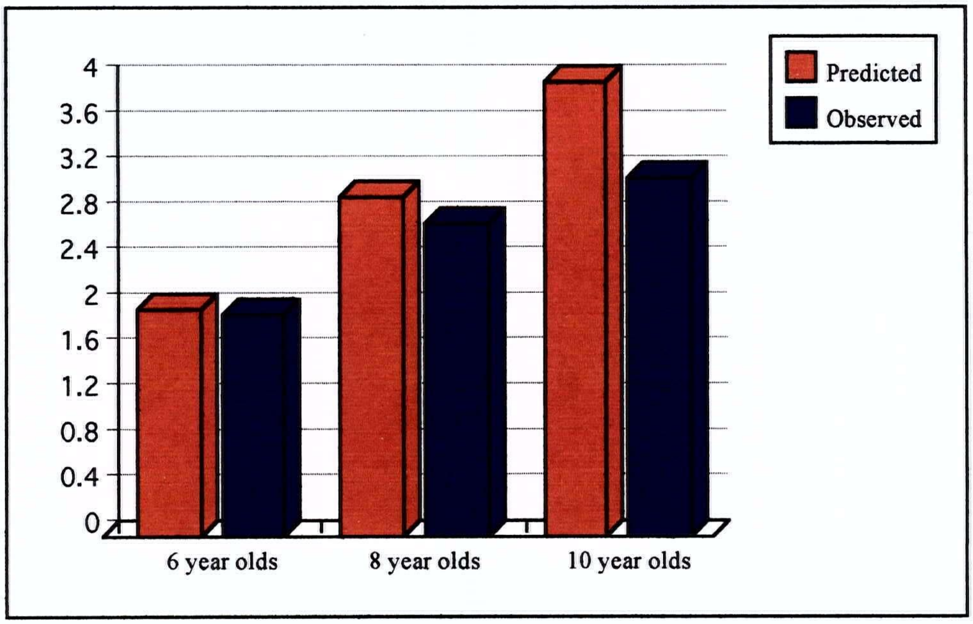


Figure 1. Distribution of total performance scores (predicted and observed) by age.

Analyses of Variance

A one-way analysis of variance for gender was performed to determine the effect of gender on the overall Performance Scores (i.e., the total number of tasks passed on the measure). The results indicated no gender effect in overall performance on the task battery ($t\ (1,59) = .17$, $p = .86$). Consequently, boys and girls were treated as one group in all subsequent analyses.

To determine if there is a significant age-level effect, a one way analysis of variance (**ANOVA**) was applied to the mean total performance scores achieved at each age. The results indicated a significant effect for age, $F\ (2,59) = 27.91$, $p = .000$. The Levene Statistic test was administered to test the homogeneity of variance. The homogeneity of variance assumption was violated for the performance score (Levene Statistic = 4.52, $p = .02$). Borg and Gall (1989) claimed that "parametric tests provide accurate estimates of statistical significance even under conditions of substantial violation of the assumptions" (p. 548). Therefore, it was considered justifiable to proceed with the analysis of variance.

Post-hoc comparisons were then conducted to specifically locate where the age differences occurred. With alpha set at .05, Tukey's Honestly Significant Difference (HSD) test was applied for this purpose and the results showed significant differences between each age group on performance scores.

Test for linear trend. A trend analysis was performed to test the hypothesized linear relationship between age and level of reasoning. The results on the Performance score indicated a significant linear trend ($F\ (2,59) = 1.99$, $p = .16$) with non-significant deviations from the predicted linear trend. Although there is an indication at the 10-year-old level of a decrease in mean level score, no curvilinear trend was observed. Figure 2 graphically compares the predicted and observed performance scores by age in linear form.

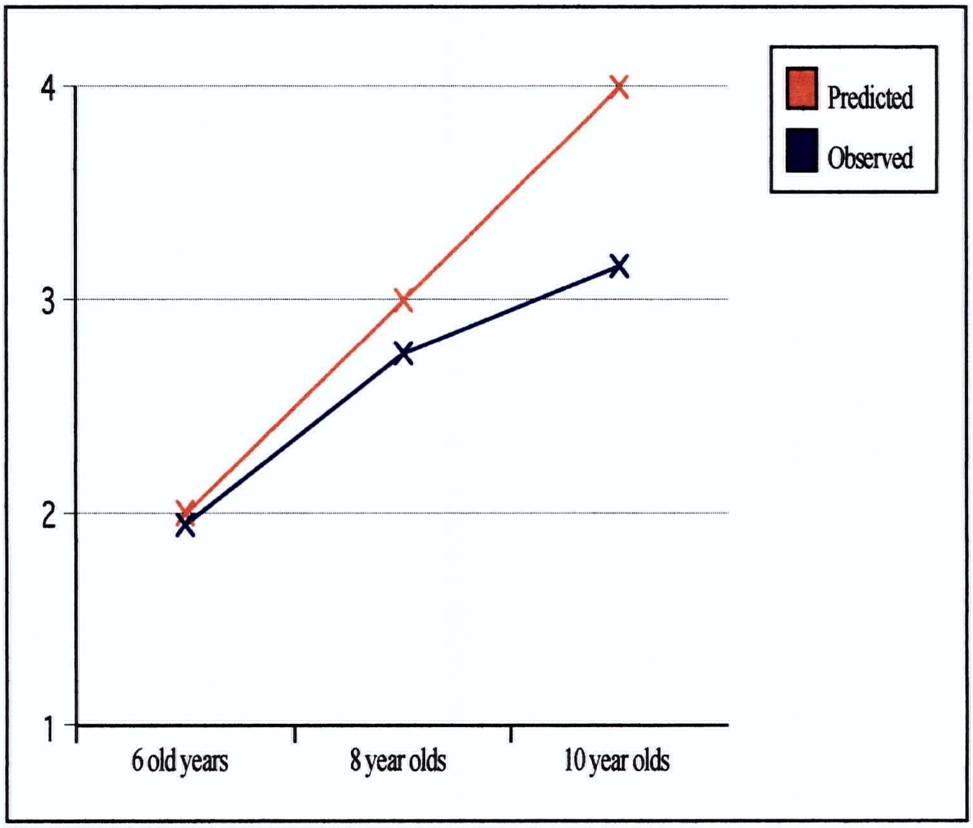


Figure 2. Observed performance scores achieved by the three age groups on the buoyancy measure in relation to the parameters of the predicted linear trend.

Analyses of Children's Developmental Scores on the Buoyancy Measure

Descriptive statistics

My first statistical analysis was to obtain an overall grand mean developmental score and standard deviation for each age group. Observed means (standard deviations) for 6-, 8-, and 10-year-olds were .75 (.23); 1.44 (.23) and 1.95 (.34), respectively. In **Figure 3**, the observed developmental scores are represented graphically and are compared with the predicted developmental scores which are based on the expected age-level responses consistent with Case's model. Predicted developmental scores established for 6-, 8-, and 10-year-olds were 1 (unidimensional), 2 (bidimensional), and 3 (integrated bidimensional) thought respectively.

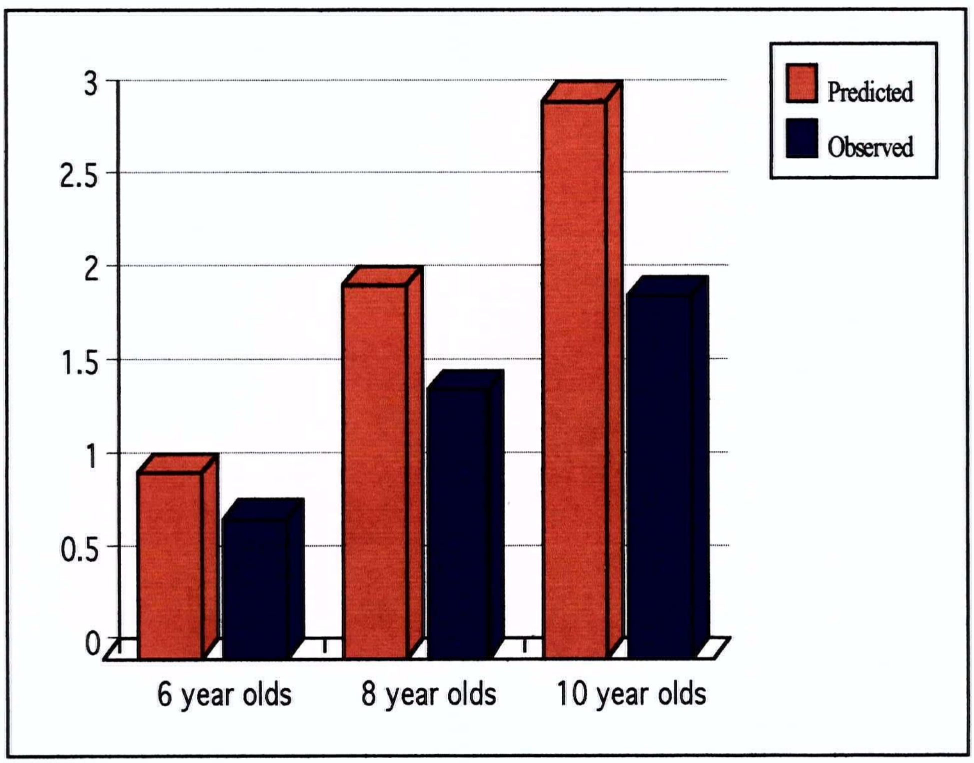


Figure 3. Distribution of developmental scores (predicted and observed) by age.

The mean developmental scores for each age group on each of the five buoyancy tasks are given in Table 5.1. The means for the first three tasks were very close within the 6- and 8-year-old group but fell slightly on the last two tasks. By contrast, the 10-year-old means were close across all five tasks.

Table 5.1

Observed Mean and Standard Deviation Developmental Scores by Age Group on each Buoyancy Task

	Task 1 (Level O) Predimensional	Task 2 (Level 1) Unidimensional	Task 3 (Level 2) bidimensional	Task 4 (Level 3) integrated bidimensional	Task 5 (Level 4) univectorial
6 years					
M	.81	1.03	.88	.65	.38
SD	.41	.34	.31	.42	.23
8 years					
M	1.48	1.86	1.81	1.01	1.03
SD	.53	.35	.19	.35	.38
10 years					
M	1.84	2.34	1.98	1.92	1.67
SD	.46	.25	.31	.79	.59

Figures 4, 5, and 6 graphically compares the predicted and observed developmental scores by age on each of the 5 buoyancy tasks.

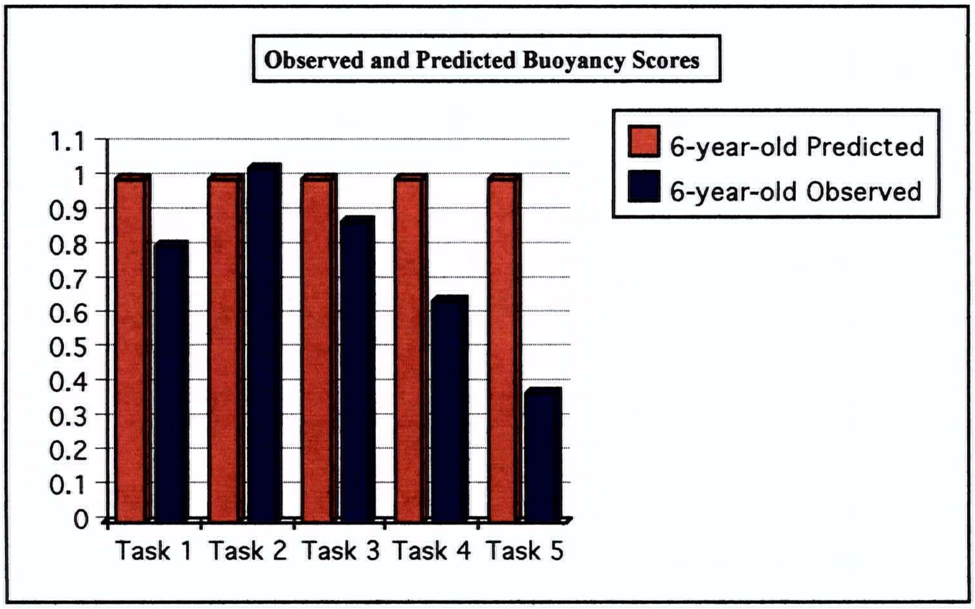


Figure 4. Cross-task consistency achieved by 6-year-olds on the buoyancy tasks in relation to the predicted level of reasoning characteristic of this age level.

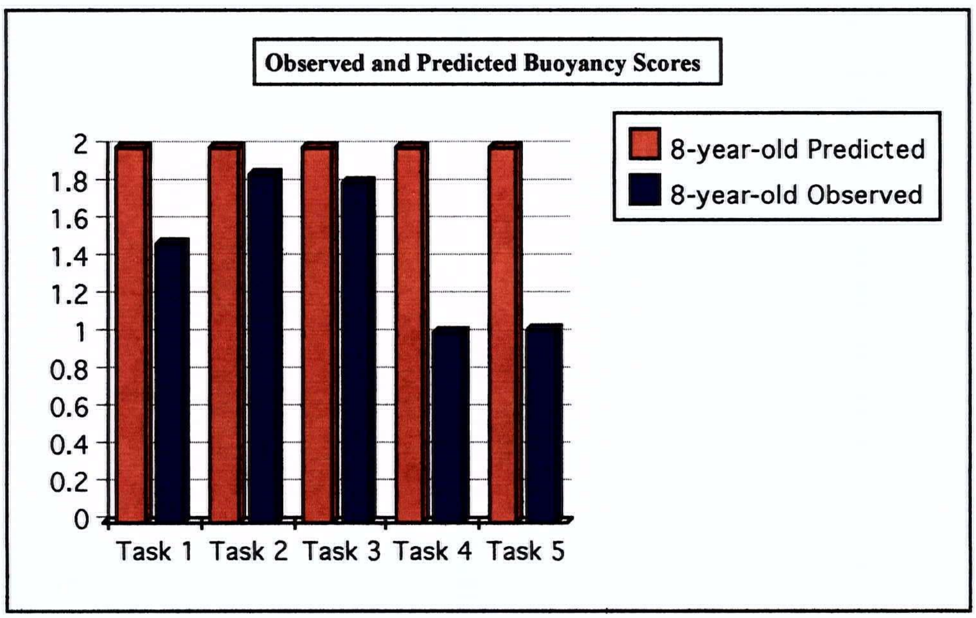


Figure 5. Cross-task consistency achieved by 8-year-olds on the buoyancy tasks in relation to the predicted level of reasoning characteristic of this age level.

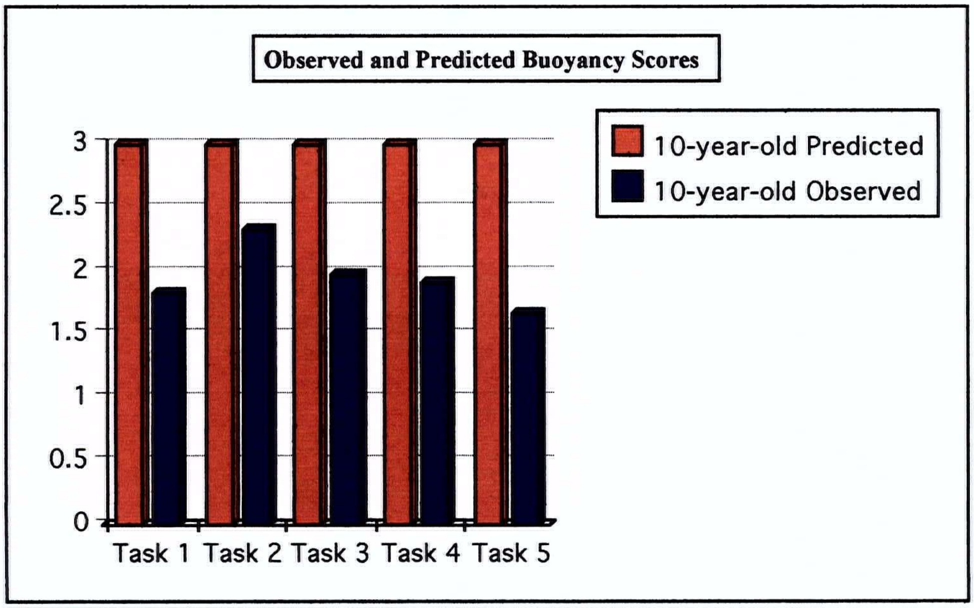


Figure 6. Cross-task consistency achieved by 10-year-olds on the buoyancy tasks in relation to the predicted level of reasoning characteristic of this age level.

Analyses of Variance

A one-way analysis of variance for gender was performed to determine the effect of gender on the developmental scores (i.e., the mean scores reflecting each age groups' level of reasoning). The results indicated no gender effect in grand developmental mean scores on the task battery ($t(1,59) = .66$, $p = .51$). Consequently, boys and girls were treated as one group in all subsequent analyses.

To determine if there is a significant age-level effect, a one way analysis of variance (**ANOVA**) was applied to the developmental scores achieved at each age. The results indicated a significant effect for age, $F(2,59) = 96.60$, $p = .000$. The Levene Statistic test was administered to test the homogeneity of variance. The homogeneity of variance assumption was not violated for the developmental scores (Levene Statistic = .87, $p = .42$).

Post-hoc comparisons were then conducted to specifically locate where the age differences occurred. With alpha set at .05, Tukey's Honestly Significant Difference (HSD) test was applied for this purpose and the results showed significant differences between each age group on developmental scores.

Test for linear trend. A trend analysis was performed to test the hypothesized linear relationship between age and level of reasoning. The results on the developmental scores indicated a significant linear trend (F (2,59) = 1.43, p = .24) with non-significant deviations from the predicted linear trend. Although there is an indication at the 10-year-old level of a decrease in mean level score, no curvilinear trend was observed. Figure 7 compares the predicted and observed developmental scores by age in linear form.

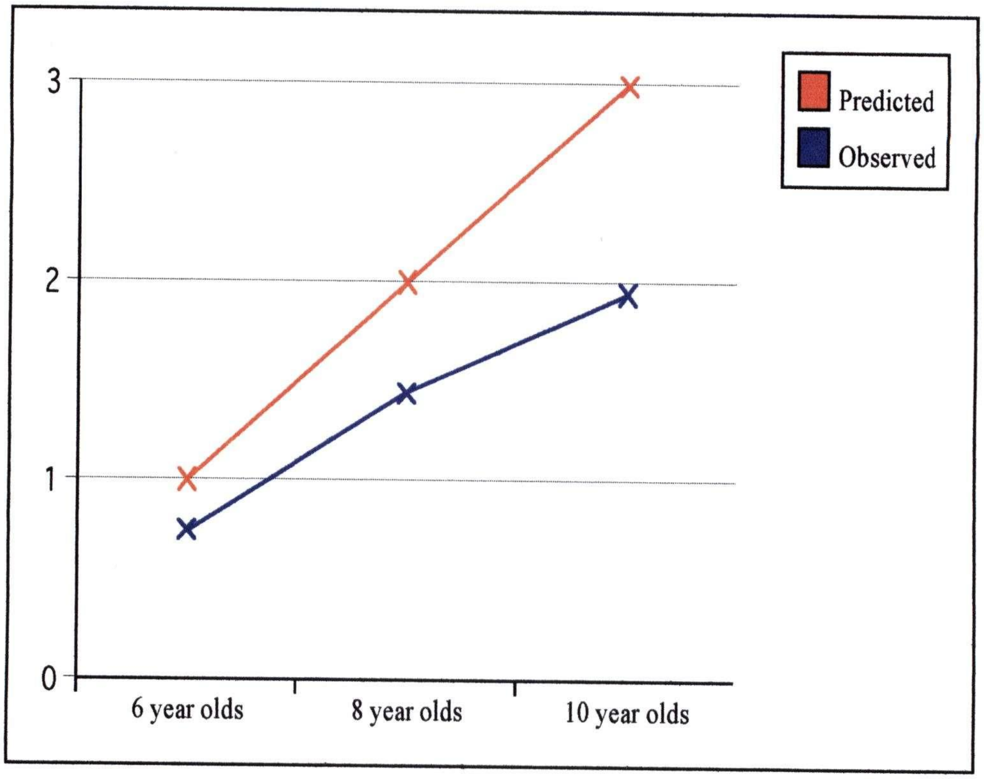


Figure 7. Observed developmental scores achieved by the three age groups on the buoyancy measure in relation to the parameters of the predicted linear trend.

All participants successfully passed Task 1 which served as the basal task and all participants failed Task 5 serving as the ceiling on the Buoyancy Scale. Table 5.2 summarizes the percentages of participants scoring above, below and at the hypothesized level on the Buoyancy Measure. The results indicate that each group performed close to the age-level expectations on the Buoyancy Measure. However, the performance of the 10-year-old group is slightly lower than the theoretical expectation. Possible reasons for this deviation will be addressed in Chapter 6.

Table 5.2

Observed Task Performance (Predicted) for Each Age Group

Group	Task 1 (Predimensional)	Task 2 (unidimensional)	Task 3 (bidimensional)	Task 4 (integrated bidimensional)	Task 5 (univectorial)
6-year-olds	100 (100%)	90 (100%)	5 (0%)	0 (0)	0(0)
8-year-olds	100 (100%)	100 (100%)	80 (100%)	0(0)	0(0)
10-year-olds	100 (100%)	100 (100%)	85 (100%)	30 (100%)	0(0)

In conclusion, an item response chart was tabulated to show the number of passes obtained by each age group on each of the 20 items on the Buoyancy Measure. These scores were obtained by calculating the total number of performance scores that were achieved separately at each age level on each of the 20 buoyancy problems on the measure. In order to receive a performance score on each problem, the success criterion for each problem was a correct buoyancy prediction that was supported by an appropriate justification that reflected the level of dimensional reasoning that each task required. The purpose for conducting such an analysis was to pinpoint particular items that may have caused some difficulty among participants or age groups in general.

Table 5.3

Performance Scores Achieved by Age Groups on each Task Item

Task Items	6-year-olds	8-year-olds	10-year-olds
1.1(rock)	20	20	20
1.2 (cork)	20	20	20
1.3 (soap)	19	18	20
1.4 (ball)	19	20	20
2.1 (bowl/potato)	16	19	20
2.2 (hat/coin)	19	20	20
2.3 (foil shapes)	19	20	20
2.4 (wood prisms)	15	17	20
3.1 (carrot/parsnip)	1	**10**	**10**
3.2 (orange/beet)	1	16	17
3.3 (sugar cube/wood block)	0	**15**	**15**
3.4 (ball/marble)	1	19	20
4.1 (egg)	0	1	**5**
4.2 (grape)	0	0	**4**
4.3 (rosewood)	0	1	**7**
4.4 (lime)	0	0	**7**
5.1 (cranberry)	0	0	0
5.2 (blueberry)	0	0	0
5.3 (duck)	0	0	0
5.4 (kiwi)	0	0	0

Note. Items of apparent difficulty are indicated in bold.

Results of this study will be discussed in the following chapter.

CHAPTER 6: DISCUSSION

Physical science is a particularly challenging subject area in which to achieve conceptual understanding. There is already sufficient evidence in the literature to suggest that children at both the elementary and secondary school level experience difficulties in learning physical concepts, one in particular being density (Bloom, 1995; Kohn, 1993; Piaget & Inhelder, 1942/1974; Smith, Carey & Wiser, 1985; Woodruff & Meyer, 1995). This educational concern raises an important question of how to design more effective approaches to teaching that will facilitate a conceptual understanding of such complex concepts. What became evident in the review of literature was a need for more developmental studies to be conducted within a theoretical framework that articulated the nature of children's representations of a specific concept in the domain of science at various points in their development. Understanding the developmental progression of a specific concept such as buoyancy will facilitate instruction that is developmentally appropriate. Such information would provide a basis for the "optimal match" (Donaldson, 1978) between learner and the curriculum.

The major goal of this study was to chart the developmental path of children's understanding of buoyancy over the course of their middle childhood years specifically for the purpose of providing developmental guidelines for the teaching of physical concepts. Using Case's (1992) framework for the progression of children's thinking in the domain of science, this study had three objectives:

1. Build a structural model of children's developing understandings about buoyancy using classroom-based data.

2. Design and administer a multilevel set of buoyancy tasks to test this hypothesized developmental sequence.

3. Identify conceptual differences in children's understanding of buoyancy within this cognitive-developmental framework.

An analysis of the classroom-based data gathered in the first phase of the study confirmed the possibility that children's reasoning could be categorized into various levels of dimensional thought proposed by the theory - unidimensional, bidimensional and integrated bidimensional. Furthermore, the research findings were encouraging in that conceptual changes were observed to occur around the age levels of 6, 8, 10 and 12 years which were consistent with the neo-Piagtian model theorized by Case (1985, 1992). Thus, a structural model was constructed with the objective of describing qualitatively different substages of children's understanding of buoyancy at each of these age levels.

The main purpose for designing and administering the Buoyancy Measure was to provide a more rigorous empirical demonstration that children's understanding changed systematically with age in a progressive manner as hypothesized by Case (1992). The five buoyancy tasks were specifically designed to assess children's movement from predimensional through to abstract thought in understanding the way in which opposing factors such as weight, shape, size, volume and density can affect an object's buoyancy. Twenty children each of ages 6, 8, and 10 were individually administered the battery of tasks in an interview setting. An objective scoring system was established using Case's metric for classifying different levels of reasoning. Each participant's response was assigned to one of the five levels of dimensional reasoning.

The results of this formal investigation confirmed that children's understanding of buoyancy did progress through the developmental sequence as hypothesized. The progression from predimensional through to integrated bidimensional reasoning captured the general developmental pattern of children's understanding of buoyancy across the three age groups. In addition, children's responses to the buoyancy tasks provided consistent support for the age-level postulates of Case's (1992) developmental model. This support was manifested both in the identification of critical factors offered by children in their explanations of buoyancy and in the way children coordinated these factors. To recap briefly, neo-Piagetian theory relies heavily upon content-related information in response to a specific concept under investigation in order to analyze the levels of performances in terms of their cognitive structural complexity. The differentiation, coordination and eventual integration of a minimum of two factors reflect the underlying dimensional structure of children's explanations of buoyancy. This interpretation of a cognitive structure provided a basis for developing scoring criteria to assess the level of children's reasoning.

From a structural standpoint, prototypical responses of the 6-, 8-, and 10-year-old participants reflected this "dimensional" structure characteristic of children's thought in the quantitative domains of mathematical and scientific reasoning, for example, on the balance beam task (Case,1985, 1992; Marini, 1992). This interpretation of a cognitive structure provided a basis for developing scoring criteria to assess the level of children's reasoning. Cognitive structures represent a relation between the child's way of thinking and the content on which the thinking is focused. Content itself depends heavily upon a child's experience and development. Children drew upon their experiences to explain such physical phenomena. This was particularly noticeable when they found tasks difficult; children would construct a conceptual understanding usually more perceptual in nature by attempting to relate what they already knew or had experienced about buoyancy. A typical example of this appeared in one 6-year-old's explanation for why he thought an egg would float in ordinary water and not salt water (Task 4.1): "It's round... and this is clear water and something that was round floated in water." He was referring to an earlier problem in which the tennis ball floated in the large container of water. Another 6-year-old based his prediction on what he had experienced at home: "My brother tried cooking eggs in ordinary water and they always drowned."

From an analytical viewpoint, the results of the study were encouraging in that a dimensional analysis can be a quite useful gauge for predicting age-related performance in the domain of science regarding children's conceptual understanding of a physical concept like buoyancy. Generally speaking, prototypical responses of 6- and 8-year-old participants reflected the "dimensional" level of thought predicted for their age. However, the percentage of children who reached the integrated bidimensional level of understanding of buoyancy by the age of 10 years was noticeably smaller than the percentage of participants at ages 6 and 8 who reached the expected unidimensional and bidimensional levels of understanding, respectively.

Regarding the 6-year-olds, 10% (2 out of 20) failed to meet the expected performance for that age on the buoyancy measure by failing Task 2 which required unidimensional reasoning prototypical for that age level. Five percent (1 out of 20) of the 6-year-old responses demonstrated an advanced level of understanding by passing Task 3 requiring bidimensional reasoning prototypical of 8-year-old thought. In reference to the 8-year-olds protocols, 20% (four out of 20) failed Task 3 which required bidimensional reasoning prototypical for that age level and 0% scored at a higher level of understanding.

Seventy-percent (14 out of 20) of the 10-year-olds failed to achieve the expected level of performance on the Buoyancy Measure for that age. Contrary to expectations, only 6 10-year-olds passed Task 4 which was designed to assess integrated bidimensional thought prototypical of that age group. Interestingly, this 10-year-old phenomena has already been encountered in other studies that have been conducted within Case's developmental framework. For example, in studies investigating children's numerical (Okamoto & Case, 1996), spatial (Dennis, 1992) and narrative (McKeough, 1992) understanding, the percentage of children who reached the integrated bidimensional thought by the age of 10 years was smaller than the percentage of children at the ages of 6 and 8 who reached the prototypical levels of unidimensional and bidimensional thought respectively. While the majority of 6- and 8-year-old results confirm theoretical predictions, it appears that a lesser percentage of 10-year-olds seem capable of reaching the integrated bidimensional thought prototypical of that age group.

According to Dennis (1992), this datum should actually be taken as a confirmation of the model and not as a refutation of it. She argues that the underlying variable against which neo-Piagetian task analyses are gauged is working memory capacity, not age, and the same slowdown of growth occurs in this variable during the 10-year-old age range. In her neo-Piagetian study investigating the development of children's drawing ability in terms of their visual-spatial representations, the 10-year-olds performed similarly to the 8-year-olds on a set of five drawing tasks designed to measure varying levels of pictorial structures produced by children across the ages of 4, 6, 8, and 10 years (Dennis, 1987, 1992). The absence of a developmental difference between these two age groups was also paralleled by a similar absence of difference in their mental processing limitations, as measured by two working memory tasks. While children aged 4, 6, and 8 demonstrated working memory capacities consistent with theoretical expectations, the 10-year-old's capacity fell short of the expected level hypothesized by the model. Hence, Dennis (1992) concluded that the difficulty experienced by the 10-year-olds in her study on the drawing task specifically designed to complement that age group's ability according to the theory might be attributed to their relatively low working memory capacity.

Dennis's argument is somewhat persuasive since the complexity of tasks that have been designed to measure integrated bidimensional thought across the domains of number, narrative and space anticipate that 10-year-olds are capable of manipulating four objectives known as "goal stacks" as they worked on solving a problem. This may not be a true index of a 10-year-old's working memory capacity. In light of this compelling argument, the 10-year-olds' overall performance on this buoyancy measure can be still viewed as supporting the general theoretical model since a statistical analysis of the data reported significant differences between each age group on both Performance and Developmental Scores.

Another unexpected result in the older children's performance was the percentage of 10-year-olds failing to pass Task 3 which required bidimensional thought prototypic of 8-year-olds. Three children (15%) failed to reach bidimensional thought; their performance was two substage levels below the expected level for that age group. The reason could most probably be related to a task "noise" effect on one of the items in the buoyancy problem for that level which proved to be problematic for approximately half of the participants. Two misleading factors of a linear and symmetrical nature influenced children's buoyancy prediction and justification for the critical pair (carrot and parsnip) in item 3.1. What was expected on this task was for children to compare the vegetables' substances since weight and shape were held constant. Instead weight distribution and to a lesser extent a comparison of length surfaced as confounding factors in children's reasoning on this task which caused them to make incorrect "float" judgments for the carrot. Moreover, with the criterion for passing each task level set at 75% (i.e., 3 out of 4 task items), it made it difficult for these students to achieve a performance score despite demonstrating their ability to reason at the required bidimensional level.

Notwithstanding a few problematic task items on the buoyancy measure which will be further discussed at a later point in the chapter, the results in general suggest that children's conceptual understanding of buoyancy did develop in the way that was hypothesized, both in the order of the structural development of conceptual structures (i.e., unidimensional, bidimensional & integrated bidimensional) and at the predicted age levels. Therefore the proposed developmental sequence in children's understanding of buoyancy was empirically validated. For the most part, each age group demonstrated prototypical reasoning unique to each age level.

Children's General Approach to the Buoyancy Tasks

During the interview sessions, it became very apparent that all the participants thoroughly enjoyed the hands-on activities and the opportunity to actually test their buoyancy predictions. The opportunity to handle and examine the objects helped to facilitate children's decision-making and no child was reluctant to make a buoyancy judgment. Providing explanations proved more challenging particularly as the tasks became more difficult. However, with the help of probes and time to think through their justification, all participants with the exception of two 6-year-olds were able to justify their buoyancy predictions on all five buoyancy tasks.

Interestingly, there was very little discrepancy among the three age groups' ability to make accurate buoyancy predictions on each of the 20 task items even if they were unable to demonstrate the expected level of reasoning for that particular problem. The following mean scores of 13.5, 14.7 and 15.7 reflect the number of correct buoyancy predictions obtained by the age groups, 6, 8, and 10 years respectively. These scores suggest that children in general, irrespective of age, appear to have a "common sense" understanding of density in that they do not always rely on an object's weight when making buoyancy judgments. Research findings from earlier density studies (Kohn, 1993; Smith et al.,1985) suggested that children as young as 3 years may have some conception of density, albeit in a global and an undifferentiated fashion from other critical factors such as weight and volume. An educator's goal therefore is to promote a transition from this implicit knowledge to an explicit level of understanding of substance properties.

Generally speaking, all sixty participants were able to maintain focus and interest throughout the complete interview session. However, Task 5 proved extremely challenging for the younger children, not so much in making a buoyancy prediction but in trying to justify their choice. The majority of 6-year-old participants began to lose their concentration and resorted to perceptual factors at this abstract level. Only two 6-year-olds made no attempts to offer an explanation and literally stated : "I don't know" or "You've got me there!"

The following section provides a detailed analysis of children's performance on the buoyancy measure at the three different age levels of 6, 8, and 10 years. It will examine children's responses to the set of five tasks of varying complexity from both a structural and conceptual perspective. A *structural* perspective will investigate the way children organize and structure their knowledge about what determines an object's buoyancy in a fashion that makes sense to them. A *conceptual* perspective will focus on their knowledge representations of buoyancy in terms of the beliefs and/or naive theories they construct to make sense of this phenomenon. Common age-typical patterns of understanding of buoyancy will be articulated as they relate to each task level. The similarities and differences in children's conceptions across the age groups will also be included in the discussion.

Reference will be made to the problems encountered by children on two of the buoyancy problems on the measure (task 3.1 & 3.3) and how misleading factors of a perceptual nature influenced children's responses causing many participants (n= 30) to make incorrect buoyancy judgments and justifications. The section will conclude with a short summary of the developmental progression in children's progression from simple conceptions of buoyancy defined in terms of perceptual factors to more complex notions of density in terms of how substance properties effect an object's buoyancy. Children's conceptions of buoyancy are based on the coordination of important buoyancy factors offered in their explanations. This captured the general pattern of reasoning at all three age levels in children's attempts to explain why they think certain objects would float.

Six-Year-Old Performance on the Buoyancy Measure

As predicted, six-year-olds demonstrated unidimensional reasoning in their explanations for what determined an object's buoyancy. Structurally, this means that they were able to assemble a "unidimensional" structure in that one variable was used to draw a conclusion about another. At this stage of development, conceptions of buoyancy are generally associated with an object's weight (quantity of matter) as opposed to its density (mass of any substance). With most 6-year-olds, shape attributes were most commonly coordinated with weight when all buoyancy factors were treated as variables in Task 1. While still unidimensional in their scientific reasoning, eight out of the 20 6-year-olds made some reference to an object's substance in terms of its texture (soft/light or hard/heavy) and four children judged an object's weight based on its "heavy/light" material. The following responses represent examples of this kind of unidimensional reasoning: (1) "The cork feels light and soft. You can squeeze it"; (2) "The soap is heavy and hard"; (3) "The cork is light because it's wood and wood floats." This coordination of weight with substance properties suggests that some 6-year-olds are beginning to associate weight with an object's density. Such a shift in thinking becomes more prevalent in 8-year-old conceptions of buoyancy.

In Task 2, in which the weight of paired objects (hollow vs solid) was held constant, all 6-year-olds continued to represent unidimensional thinking by coordinating two shape attributes. The most common shape attributes upon which children judged an object's buoyancy was whether the object had a hole in the middle and resembled a boat in shape. Further prompting induced four 6-year-olds to mention that the bowl-shaped object contained air inside the hole but they were unable to articulate how this helped to make it float. By contrast, the notion of air inside the bowl-shaped objects could not be elicited from the remaining sixteen 6-year-olds. Interestingly, weight was usually coordinated with substance in their justifications for why the solid object would sink. These data suggest that six-year-olds appear to possess a naive theory that bowl-shaped or hollow objects float while solid objects that are "full of stuff" sink.

However, 6-year-olds do not appear to be deceived by solid wooden blocks; they share a common belief that anything made of wood floats. This was clearly manifested by their successful "float" prediction for two wooden solids (cylinder and pyramid) of equal size and weight in Task 2.4. Only three out of the 20 6-year-olds made an incorrect "sink" prediction. Half of the children who predicted correctly based their decision on the round shape of the cylinder and pyramid while the other half referred to the light weight of the wood.

Task 3 was designed to test for the effects of substance and size on an object's buoyancy. Children were required to demonstrate bidimensional reasoning in their explanations which is prototypical of 8-year-old thinking. In the first problem, participants were asked to compare a carrot and parsnip of equal weight and of similar shape. Although unable to reason bidimensionally, 6-year-olds were more accurate in their buoyancy judgment on this problem than the two older age groups. Surprisingly, thirteen 6-year-olds were able to accurately predict that the parsnip would float. Nine of these children based their prediction on a size and substance comparison of the two vegetables and the remaining four based their decision on a size and shape comparison.

Contrary to 8-and 10-year-old thought, most 6-year-olds believed that the "bigger round end" of the parsnip would help make it float **not** sink. Very few 6-year-olds were deceived by the uneven weight distribution of the parsnip. By contrast, half of the remaining 8- and 10-year-old participants (exactly 10 from each age group) were misled by this perceptual feature and failed to make the expected substance comparison between the two vegetables resulting in an incorrect prediction. This particular problem (Task 3.1) caused participants more difficulty than any other task item on the measure. For the present, it is important to flag this aspect of the data as being of significance.

On the second problem (3.2 orange vs. beet), most 6-year-olds compared substances and determined which of the two felt softer (squishier) and therefore lighter. Since both objects were round (not linear in shape like the carrot & parsnip), 6-year-old predictions were based on a weight and substance comparison in a typical unidimensional fashion. Although unable to demonstrate bidimensional reasoning for why the orange would float, these data provide further support in that 6-year-olds are capable of making a distinction between mass of matter and mass of substance (i.e., density) when weight and shape, in particular are held constant. It is important to mention, at this point in the discussion, that children were given the opportunity during the interview to weigh each object so that they could visibly confirm that each critical pair weighed the same.

If the notion of substance properties had not yet surfaced in a 6-year-old's repertoire of buoyancy factors, then predictions were usually based on superficial attributes, such as bumps on the parsnip or lines on the carrot. These 6-year-olds seemed to want to find some perceptual flaw or blemish on the vegetable that would let in water and consequently make it sink. One example of this type of response was offered by a six-year-old in her justification as to why she thought the orange would sink: The orange has tiny holes in it so it will breathe in water.

In task 3.3 (sugar cube vs wood block), a perceptual illusion, known as the size-weight illusion, was clearly a factor which caused a number of 6-year-olds to make an erroneous "float" judgment for the sugar cube. Since weight is not held constant with this pair of objects, half of the 6-year-olds mistakingly judged that the sugar-cube would float because it was smaller and lighter than the wooden block. It was interesting to see how powerful this perceptual illusion was in not only misleading them to believe that the weight of the wood block was denser than it actually was but also in temporarily blocking children's conceptual belief that wood floats. It was only after testing their prediction that children referred back to their common belief that wood floats. The data suggest that when both weight and density are treated as independent variables in a problem, many 6-year-olds are unable at this point in their development to differentiate the weight of matter from the weight of substances. Piaget and Inhelder (1942/1974) were the first to recognize this concept of "global quantity" in young children's thinking. Interestingly, Kohn (1993) found that 3-year-olds were more accurate in their "sink" predictions than 4-5-year-olds when asked to judge the buoyancy of dense, light weight objects.

These errors in judgment raise the question of what happens when the properties of volume and weight (mass) are pitted against the more relevant property of substances (density). Common perceptual illusions, such as the size-weight illusion and the weight-density illusion, occur at least in part because we expect certain properties to be correlated in the everyday physical world. According to Ohwaki (1953), young children do not show evidence of the size-weight illusion until the ages of 4 or 5 years. Piaget (1961/1969) discussed factors that might be involved in experiencing the size-weight illusion, and noted that the illusion increases with age up to 11 and 12 years at which point it then declines.

Interestingly, the explanations offered by the ten 6-year-olds who predicted correctly on this paired-object item (sugar cube, wooden block) reflected the antithesis of the size-weight illusion: the big heavier block would float and the small light sugar cube would sink. These children probably relied more upon their worldly experiences of placing objects of varying sizes in water which helped them to see that there was no consistent pattern related to the size of objects in determining whether it would float or sink. Generally speaking, 6-year-olds preferred to judge an object's weight on shape attributes rather than its size.

The general pattern of 6-year-old reasoning on Task 4 (testing an object's buoyancy in plain water and salt water) was related to the notion that salt water had "salt power" that helped to push up the objects. Six-year-olds intuitively knew that it was something to do with salt added to the water that made things float in that liquid and not regular water. Prototypical explanations offered by this age group centered on the notion that "the salt pushes it up." How or why prompts asking for further clarification proved unsuccessful. A few attempts were made to explain this "salt power" but perceptual factors were often used to explain this phenomenon. For example, several children referred to the salt spinning around in the water like a whirlwind and that helped to push the object up. Another innovative justification offered by a 6-year-old boy represented a more conceptual and sophisticated explanation. On discovering that he had made an incorrect prediction about the rosewood floating in ordinary water, he commented: "All the salt turned into particles and they are pushing it up. It's like men - they need air to push their jets up."

Task 5 proved to be extremely difficult for all 6-year-old participants. The amount of information required to solve the two problems in this task was far too much for children of this age to process at once. Consequently, the task placed far too many demands on a 6-year-old's working memory capacity which may have been a factor responsible for lowering the level of reasoning to a predimensional level. Perceptual factors replaced any attempts to reason scientifically. For instance, several children quite clearly stated that real ducks float on salt water and so incorrectly concluded that the small rubber duck would float in both salt water and the molasses. Some children simply made either a weight or substance comparison between the two objects, the equivalent of predimensional thought. Only two children were able to maintain the predicted level of reasoning (unidimensional) for their age on this task.

Summary of 6-year-old results. The critical factors generally used by 6-year-olds in their reasoning about buoyancy are weight (mass), shape and substance texture. A common naive conception of six-year-olds is that boat-shaped objects with a hole in the middle float while solid objects sink. A few children (n = 4) commented on the fact that air was in the middle of boat-shaped objects but, unlike the 8-year-olds, they were unable to explain how air in the objects made them float. Interestingly, 6-year-olds rarely included size as an important factor in their explanations of buoyancy. Intuitively, they seemed to know that it could not be reliably coordinated with an object's weight to make a correct buoyancy judgment. This may be a result of a naive conception maintained by this age group, specifically that large, heavy objects are just as capable of floating as small, lightweight objects. Alternately, the data provide substantive evidence that 6-year-olds are also developing an awareness of substance properties as reflected in their references to texture (i.e., soft or hard). Hence, children at this age appear to have a “common sense” understanding of density in that they are beginning to differentiate between properties of objects (e.g., weight, shape, size) and properties of substances (e.g., weight, textures, materials).

Eight-Year-Old Performance on the Buoyancy Measure

As predicted, 8-year-old responses on the buoyancy tasks consistently reflected bidimensional reasoning. Structurally, this means that they were able to consider two factors as they related to weight in making a judgment about buoyancy, thus thinking in a bidimensional manner. Whereas 6-year-olds essentially relied on shape attributes and to some extent substance textures to judge an object’s weight, 8-year-olds paid closer attention to the actual substance materials (e.g., plastic, wood) which they qualified as heavy or light stuff. Even when some children did not know that cork was made from wood, they would often substitute another lightweight material such as styrofoam. One student even suggested that the cork had foam in the middle.

In 8-year-old responses, a second factor was then added to this first dimension (i.e., weight judged by substance material) which raised the level of reasoning to bidimensional. A common second factor characteristically used by 8-year-olds to quantify the weight of substances is the “air theory” factor. Both 8- and 10-year-olds believe that if an object contains air it will float because air is lighter than water. An alternate pattern of bidimensional thinking represented by 8-year-olds was to consider the texture of the object suggesting the presence of air in soft or squishy textures and the converse in hard, solid textures.

The terms *hollow* or *solid* were commonly used in 8-year-old explanations, particularly in task 2 which tested for the effects of an object's shape when the weight of paired objects was held constant. The qualitative difference in 8-year-old explanations from those of 6-year-olds was the noticeable reduction in the number of shape attributes articulated. At this age level, buoyancy was judged on whether an object was hollow or solid and then linked to the air theory to form bidimensional reasoning. A prototypical example offered by this age group for problems in Task 2 assumes the following pattern of reasoning: "This foil-shape is hollow in the middle and so air can get inside it. And the ball of foil is all crumpled together.. it made all the air come out." This hollow vs solid factor accompanied by the air theory notion indicates that 8-year-olds appear to possess an intuitive understanding of density, albeit primitive, and are capable of making a weight-density distinction. When the weight of paired objects is held constant and shape is the variable, the data revealed that 8-year-olds were able to extend their reasoning beyond shape attributes and focus more on substance properties when making buoyancy judgments.

Very few 8-year-olds were deceived by the two wooden solids in Task 2.4. Only three 8-year-olds offered an incorrect "sink" judgment which was accompanied by a justification that was more of a perceptual nature. Just like the three 6-year-olds who also predicted incorrectly on this problem, they based their prediction on the solid and heavy appearance of the cylinder and pyramid. In other words, a weight-density perceptual illusion challenged their fundamental belief that wood floats. All remaining seventeen 8-year-olds were of the general consensus that the solids floated because they were made out of wood. Unlike some of the 6-year-olds, shape did not play a key factor at all in the decision-making on this task.

In Task 3, in which shape and weight were held constant, 8-year-olds consistently based their buoyancy judgments on a substance comparison for the paired objects. The common hypothesis was that if the substance feels soft and squishy, then it was made of light stuff; if it was hard or hard-packed then it was judged as heavy stuff. This represented the first dimension in their explanation which paralleled many of the 6-year-olds' reasoning. However, 8-year-olds incorporated a second dimension to further quantify the density of each substance by suggesting that soft, spongy material contains air inside that will help make it float whereas hard substances have no room for air, causing it to sink. For example, one student offered the following explanation for why the parsnip floats: "The parsnip will float because the stuff inside is almost like a sponge as it gets all the air in it. The carrot feels heavier. It's not soft in the middle. I don't think there are any air holes in it. It's hard in there." Texture combined with the air theory captured the general pattern of 8-year-old bidimensional reasoning on the buoyancy problems for Task 3.

As previously mentioned, the critical pair 3.1 (carrot vs parsnip) caused more difficulty among 8-year-olds than 6-year-olds. Only half of the group passed this task with a correct "float" prediction for the parsnip that was based on a substance comparison of the two vegetables (see above example). A common error made by the other ten 8-year-olds who failed this problem was to consider weight distribution as a critical factor which caused them to make an incorrect buoyancy judgment for the parsnip. The following pattern of reasoning represents the prototypical explanation offered by these children: "The parsnip will sink because it has a larger fatter end and so when you put it into the water the heavier part will start going to the bottom. The carrot will float because it's longer in size and this end of the carrot is not bigger than this end." Once again, perceptual factors were at play here and children were deceived by an uneven size-weight illusion in terms of the parsnip's appearance. Interestingly, their reasoning changed to a substance comparison of the two vegetables after they had tested their prediction and actually saw the parsnip float.

Comments of this nature were offered: “Maybe there is air trapped inside the parsnip and sort of grew it out wider at this end. Air is holding it up. The carrot sank because it didn’t have any air because it’s all squeezed together more (what is?) the carrot stuff.”

In 6-year-old logic, the uneven size-weight distribution of the parsnip was treated as an important factor that kept the parsnip afloat; in 8-year-old logic, it was the antithesis. These data suggest that the older children appear to be cognizant of the critical relationship that exists between weight and size (volume) in determining an object’s buoyancy. However, at this point in their development, 8-year-olds have difficulty integrating this weight-size relationship with their knowledge about the density of substances. As a result, many inconsistencies and contradictions appear in their reasoning due to an inability to integrate these two distinct basic factors. Such information suggests to educators that children at this age are ready to learn the concept of volume and learn how to relate it to the mass of substances in order to acquire a basic understanding of density.

Interestingly, when comparing the critical pair in item 3.3 (sugar cube vs wood block), the majority of 8-year-olds (n =15) were not deceived by the size-weight or weight-density illusion. Instead, they stood firm on their conceptual belief that wood floats. In twelve of these responses, a weight comparison of the two substances was clearly articulated. Moreover, two students commented that the sugar cube must be heavy for its size and yet feels light. Perceptual factors led five 8-year-olds to disregard the steadfast “wood theory” and incorrectly use the “air theory” upon which to base their buoyancy prediction. Visual evidence of the presence of air inside the sugar cube mistakingly led these children to believe that the solid wood block contained no air so would consequently sink. This erroneous justification may be the consequence of a weight-density illusion which clearly demonstrates how perceptual factors can overrule conceptual beliefs. Furthermore, five 8-year-olds based their prediction on the fact that sugar dissolves in water. Inasmuch as this is true, the interviewer redirected their thinking by explaining that the cube would either float or sink before it completely dissolved. Once this important misleading factor was resolved, these children were able to make a substance comparison.

The general pattern of reasoning demonstrated by 8-year-olds on task 4 was to offer possible theories for why salt water was better able to make objects buoyant. These theories were of a perceptual nature and reflected an extension of the 6-year-old "power of salt" saga. For example, one child considered that the salt was working as a "family" with the water in that they all worked together to push up on the egg. Several children applied the "air theory" to the liquids suggesting that the salt water had air inside it and so made objects float; another commented on the fact the salt lets off a gas that makes stuff float. Generally speaking, perceptual factors provided the foundation upon which these enterprising theories were constructed as was the case with this explanation: "It's like a cyclone in the salt water. All the salt is whirling around. It's like a twister and twisters have a whole bunch of air force... and the force of the air pushes stuff up because it's swimming around and going up."

As expected, more 8-year-olds than 6-year-olds were able to conceptualize that salt water was the heavier of the two liquids as they progressed through the four problems. These data suggests that children of this age are developing an understanding that a weight relationship exists between object and liquid. The opportunity to confirm or disconfirm their predictions on each problem may have possibly induced this learning effect within this task. Approximately half of the 8-year-old participants were beginning to perceive the effects of an object's weight on different liquid weights (i.e., relative weight). Three 8-year-olds were able to articulate their understanding of relative weight as reflected in the following explanations: (1) "The lime will sink in ordinary water because it's too heavy for that water.

And the lime will float in salt water because it's light for that water" ; (2) "I guess the grape was too heavy for the ordinary water. And in the salt water it has salt and so the salt water is a little heavier than the ordinary water " (a comment made after testing his prediction). Of the remaining seventeen 8-year-olds who were unable to articulate this new knowledge in explicit terms at this point in their development, three children appeared to intuitively sense that some form of compensation occurred between the object and two liquids but their conceptual understanding was the converse of what actually happens. They maintained the theory that the salt water was too heavy to hold up objects. Due to the complexity and demands of the task, the 8-year-old performance, as a group, represented unidimensional reasoning, one substage below their expected level of ability.

Along a similar vein, 8-year-olds performed one substage below their expected level on task 5 (which required abstract thinking) as a result of trying to coordinate perceptual factors with scientific reasoning in their response justifications. These low scores on the last two tasks were responsible for slightly reducing this age group's overall developmental score on the Task Battery (observed mean = 1.44, predicted mean = 2).

Summary of 8-year-old results. Eight-year-olds' explanations of buoyancy were associated more with the weight of the substance (density) than an object's weight per se which was characteristic of 6-year-old thinking. They were capable of explaining how two different substance properties offset weight and determine an object's buoyancy. Such data suggest that density is beginning to emerge as a separate concept at this age level, albeit in a primitive form. At this age level, the notion that the mass of substances can be quantified as light or heavy figures prominently in their descriptions of substance material. To conceptualize this understanding of density in more explicit terms, 8-year-olds use the "air theory" to differentiate between light and heavy substances. Eight-year-olds believed that if substances contain air they would float whereas solid substances have no room for air and so were predicted to sink. In fact, this "air theory" was applied to many contexts within task problems by this age group. For example, in the first two tasks, it was used to justify why hollow objects floated and solid objects sank. In task 3, when shape, weight and size were held constant, this theory was automatically applied to substances. This versatile use of the "air theory" played an integral role in 8-year-old reasoning and clearly distinguished it from 6-year-old thought.

In summary, the most significant qualitative difference between 8- and 6-year-old conceptions is that 8-year-olds are cognizant of the effects of substance on an object's weight in determining buoyancy. They demonstrate an understanding that the critical weight factor is not so much an object's mass but the mass of its substance (i.e., density). It may be that, at this point in a child's development, the true concept of density is born. The data suggest that while 6-year-olds demonstrate an intuitive understanding of density, they are still unable to clearly differentiate weight from density which confirms Piaget and Inhelder's (1942/1974) argument. Whereas 6-year-olds tended to rely more on perceptual factors that essentially described properties of the objects themselves, 8-year-olds began to differentiate weight from density in that they directly focused on substance properties to judge an object's weight in order to determine its buoyancy.

Ten-Year-Old Performance on the Buoyancy Measure

Although there was a smaller percentage of 10-year-olds (n=6) capable of reaching the integrated bidimensional thought prototypical of that age group, an analysis of the remaining 14 protocols revealed some attempts to integrate factors in a more elaborate fashion than their younger cohorts. Some forms of compensation were demonstrated between object properties in terms of how size and amount of surface area affected weight distribution. There were very few attempts to relate these factors specifically to the medium in an integrated way. Unfortunately, this form of compensation between the object properties alone failed to meet the criteria established for integrated bidimensional thought on these buoyancy tasks. To qualify as integrated bidimensional reasoning, explanations were expected to contrast the properties of objects and liquids in an integrated way. In other words, children needed to articulate how these two variables "trade off" or "compensate" for each other's weight. Very little evidence of this form of compensation was articulated by the 10-year-olds as a group. As reported earlier, only 6 10-year-olds were able to articulate this level of understanding in an integrated bidimensional fashion.

However, more 10-year-olds were capable of integrating an object's weight with size (volume) than 8-year-olds due to their conceptual representation of weight as the density of the material. For example, the following responses demonstrate attempts to integrate an object's weight and size: "It's small and heavy for its size; the ball is big but light for its size." An intuitive understanding of volume is manifested by these responses. Although these notions of volume might be described as "naive theories" (Carey, 1985), they represent a higher order understanding of density in terms of the relationships that exist between (1) weight and volume or (2) weight distribution and surface area. These data provide educators with important information in that 10-year-olds have an implicit understanding of volume that has not yet surfaced at the explicit level of understanding, that is, in the formal mathematical sense.

In the first task, ten-year-olds continued to articulate the terms *hollow* and *solid* which were used by 8-year-olds in conjunction with the air theory. However, a subtle semantic difference in the two groups' conceptual understanding was in the 10-year-olds' ability to incorporate the terms *particles* or *molecules*. In so doing, they were able to qualify an object's density in more precise terms. The following responses represent this kind of understanding: "The rock is full of particles that are heavy"; "the cork is light and has holes in it so air molecules can go inside. Air makes things rise and the bubbles from the air molecules will just shoot it up."

Interestingly, there was very little evidence of compensation between the object's density and that of the water in most 10-year-old responses on this first task. As a result most of the 10-year-old scoring fell short of level 3 reasoning (integrated bidimensional). Only one student was able to demonstrate his understanding of proportional reasoning with this explanation for why the rock would sink: "The rock is heavier than water. If there was a chunk of water as big as this rock exactly it would weigh less than this rock. (What do you mean?) The same amount of water would weigh less than the same amount of rock." His response clearly demonstrates a true understanding of volume and density. Both object and medium were completely integrated in his explanation that received a score of 4 which was equivalent to univectorial thinking prototypical of 12-year-olds.

In task 2, in which the weight of paired objects was held constant, the notion of relative weight became more evident in 10-year-old responses. In so doing, more 10-year-olds were able to demonstrate the predicted level of thinking for their age. Like 6- and 8-year-olds, shape was the most salient factor combined with the air theory but some 10-year-olds also recognized the varying density of the substances and how this affected their weight distribution on the water. The terms *thinner* or *thicker* were used to compare object densities. For instance, this explanation reflected integrated bidimensional reasoning for item 2.3: "This shape is spread out more and when it's spread out the foil is thinner. It's taking more room up on the water and the shape is bigger so it can float better. This foil is all crumpled up into a little ball and the foil is all pushed together making it smaller and heavier."

Contrary to expectation, the 10-year-olds performed similarly to the 8-year-olds on task 3; their general pattern of reasoning paralleled the same bidimensional explanations offered by the younger group. This absence of a developmental difference between the two age groups on this particular task was reflected in the mean scores of 1.8 and 1.98 for the 8- and 10-year-olds respectively. The reason for this similarity in responses was a noticeable lack of reference to the medium in the older children's explanations. As mentioned earlier, it was anticipated that 10-year-olds would incorporate medium properties into their justifications and contrast them with the objects to illustrate integrated bidimensional reasoning. Instead 10-year-old responses were generally represented by detailed substance accounts of an object's makeup which were often articulated in terms of its particulate matter (i.e., particles, molecules) but more commonly in terms of whether there was room for air in the substances. This scientific reasoning was used to quantify the density of an object as light or heavy. The presence or absence of air in substances might be described as "naive theories" (Carey, 1985) and play an integral role in both 8- and 10-year-old conceptions for what determines an object's buoyancy.

The 10-year-olds performed similarly to the the 8-year-olds on task 3.1 (carrot vs parsnip), that is, only half (n = 10) of the participants in each age group passed this problem. Whereas correct predictions were supported by an appropriate substance comparison of the two vegetables in a bidimensional fashion, incorrect predictions were based on a comparison of the even and uneven weight distribution of the carrot and parsnip respectively. Such justifications did not always represent bidimensional reasoning; some responses dropped to the unidimensional level. The perceptual salience of the parsnip's variation in size and weight distribution overshadowed the intended independent variables of size and density.

Furthermore, just as many 10-year-olds as 8-year-olds (n = 4) were deceived by the size-weight illusion on task 3.3 (wood block vs sugar cube) by making an incorrect "float" prediction for the sugar cube using this example as a justification: "The sugar cube is little and a lot lighter. The block is heavier and bigger so it will probably sink."

Of the remaining 16 students who passed task 3.3, ten were capable of making a comparison between the two substances as demonstrated by the following examples: (1) "Even though the sugar cube is smaller and has air inside it when it goes into the water it sinks because sugar cubes are supposed to sink (Yes, you know they sink but what makes them sink?) Well people don't think that sugar is very heavy but when it's packed together it is heavy"; (2) "There's so much weight in the sugar and the block is made of wood and wood floats; The wood is heavier than the sugar cube but it's probably lighter inside." These examples clearly illustrate children's ability to differentiate the concept of density from the object's mass.

Although this age group's performance on Task 4 fell short of the theoretical predictions for the 10-year-old age level, conceptual differences did emerge at this age level that were distinct from the younger 8-year-old conceptions. Counter to 6- and 8-year-olds' perceptual justifications for the power of salt in salt water, all 10-year-olds were cognizant of the fact that salt in the water made it heavier than the ordinary water. Generally speaking, the notion of relative weight did appear to emerge as children progressed through the four problems. Fourteen children misjudged the density of the grape (task 4.2) and predicted that it would float in regular water. As soon as these children received feedback on their prediction and actually saw the grape sink in ordinary water and float in salt water, they began to develop an understanding of compensation in terms of relative weight.

In addition to the 6 10-year-olds who consistently demonstrated the predicted integrated bidimensional level of reasoning, two additional participants scored at the predicted level on the third and fourth problem. Unfortunately, these two 10-year-olds failed to meet the criterion of passing 3 out of the 4 problems on this task. Only three children misunderstood the notion of relative weight by believing that the heavier liquid would sink objects, a similar phenomenon encountered in three 8-year-old protocols on this task. These 10-year-olds justified their choice of regular water by the fact that it contained air molecules as opposed to salt molecules and that the air inside the water would help to hold up the objects. Unfortunately for them, this attempt to generalize the "air theory" to liquids was unsuccessful.

What was required at this level of reasoning was for students to differentiate between the two relationships of (1) object density in relation to ordinary water and (2) object density in relation to salt water. Most 10-year-olds were unable to articulate this conception in an integrated bidimensional manner. However, some interesting data emerged from this task regarding 10-year-olds' learning potential at their developmental level. One of the strengths of this Buoyancy Measure was that children were able to test their predictions and utilize this feedback to improve their performance. The data revealed a general improvement in the 10-year-olds' performance as a group for tasks 4.3 and 4.4 which suggests that children at this age level appeared to develop a better understanding of relative weight as they progressed through the four item problems.

Due to a significant improvement in 10-year-old's predictions and level of reasoning on the last two problems, task 4 might be said to index the amount of learning 10-year-olds can assimilate at their developmental level instead of indexing their developmental capacity or optimum level (Fischer, 1980). The task analysis model utilized in neo-Piagetian studies is one that relates processing efficiency (assessed in terms of a child's working memory capacity load) to conceptual complexity. As mentioned earlier, research findings from previous studies investigating children's drawing ability and mathematical knowledge (Dennis, 1992; Okamoto & Case, 1996) revealed an absence of a difference in 8- and 10-year-olds' mental processing limitations, as measured by working memory, which consequently affected 10-year-olds' performance on tasks designed to represent integrated bidimensional thought in these domains of knowledge.

By the same token, the sample of 10-year-olds in this study also experienced difficulty in passing the buoyancy problems in task 4 which required integrated bidimensional thought. It was expected that most 10-year-olds would have been able to contrast the properties of the object and liquids in an integrated fashion. A conceptual understanding of buoyancy of this complex nature may not be a true index of 10-year-olds' representational abilities at this point in their development due to their relatively low working memory capacity. From a more positive viewpoint, however, the data does provide empirical support that 10-year-olds, with some instructional guidance, appear to be capable of achieving this level of understanding .

In the final task, 10-year-old reasoning generally reflected bidimensional thought, prototypical of 8-year-olds. Like their younger cohorts, 10-year-olds also experienced some difficulty manipulating all the information. By contrast, however, they seemed to approach the problems at this task level in a more systematic way than the younger age groups in that they made separate object and liquid density comparisons before judging which of the two objects would float on both mediums.

Summary of 10-year-old results. Prototypical explanations at this age level centered on the coordination of substance properties which paralleled the same general pattern of reasoning articulated by the 8-year-olds. However, the most distinguishing characteristic of a 10-year-old response is the inclusion of the terms particles and molecules which are generally associated with particulate matter. As a consequence, descriptions and comparisons of substances are articulated in a more elaborate manner by the older children which suggest a more advanced level of conceptual understanding of density. In addition, children at the age of 10 are capable of incorporating into their knowledge systems the notion of volume, as was apparent in their numerous attempts to integrate weight and size factors. They are beginning to see how this dimension can inform buoyancy judgments. Whereas in the earlier age levels the dimensions of size and volume may have been undifferentiated, children now demonstrate the ability to differentiate the two variables. In fact, at this point in a child's conceptual development it may be possible for educators to advance 10-year-old's understanding of the concept of volume. Moreover, their understanding of density might be further enhanced with instructional support if children of this age are made aware of the important relationship that exists between an object's weight and volume in determining its buoyancy.

Although there was some evidence of compensation between object and medium in terms of relative weight at this age level, most responses portrayed a static explanation of buoyancy that focused on the properties of the objects and mediums as separate entities. Generally speaking, it was not until they reached task 4 on the measure that this group of 10-year-olds showed their capability of making a direct relationship between object and medium by contrasting an object's weight/density to the weight of the liquid(s). In conclusion, the majority of explanations offered by this sample of 10-year-olds failed to integrate relationships between object and medium in terms of relative weight. However, a basic understanding of weight, matter and volume, essential components of density, appears to be present at this age, but difficulties are still experienced in representing relations between these variables.

Summary of the Study

What conclusions can be drawn with regard to this sample of 6-, 8- and 10-year-olds' understanding of buoyancy in this study? First, children's scientific knowledge was observed to undergo developmental changes. Younger children's associations between the variables determining buoyancy tended to be limited, more perceptual in nature and less structured. Older children's conceptual representations included more critical variables and more connections between variables were identified. Second, the results confirmed a hierarchical structure of qualitatively different conceptions as children mature which were consistent with the age-level postulates of Case's model. Consequently, three distinct forms of understanding could be articulated at the ages of 6, 8, and 10 years in the way they represented their conceptual knowledge about buoyancy.

The children's knowledge representations differed from each other on a number of dimensions: the size of their knowledge base, the interconnectedness of their knowledge and the way the concepts were coded. Whereas six-year-olds had a very limited repertoire of factors associated with buoyancy as apparent by their consistent dependency on either shape attributes or substance textures, 8-year-olds demonstrated a greater awareness of different substance properties and how they interacted with an object's weight to effect its buoyancy. At the 10-year-old level, explanations of buoyancy were more specific and less general in their descriptions of a substance's density in terms of its particulate matter. Children at this age are capable of understanding how a third variable can complicate a system. For instance, they become increasingly aware of how volume plays an integral part in the concept of density in addition to the dimensions of weight and size as reflected in their comments that an object was light or heavy for its size. Interestingly, size was not a common factor used by most 6- and 8-year-olds in their justifications; they seemed to sense intuitively that size and weight were an unreliable combination. A few children at this point in their development were able to articulate the same integrated response as that offered by many 10-year-olds (i.e, light/heavy for its size).

Another interesting observation extracted from 10-year-old response data was evidence of the process of *conceptual chunking* taking place in their knowledge representation of buoyancy, as demonstrated by the consolidation of shape and size factors which were formerly considered as separate items in younger children's mental representations. In some 10-year-old responses, these factors are recoded as a single item, namely volume. Halford (1993) firmly believed that such recoding of representational knowledge leads to greater gains in a child's processing efficiency. Case (1985) and Olson (1989) also postulated that this increasing capacity, in terms of processing efficiency, can serve to explain the development of children's representational abilities. As children mature there is a developing awareness of the reciprocal process that takes place between the properties of object and medium.

The findings of this study suggest that children, by the ages of 6 to 8 years, are developing a conceptual understanding of density as reflected by their gradual transition from considering an object's weight judged by its shape attributes to focusing more on the mass of an object's material (e.g., wood, plastic, metal) or its substance. It is also evident from the response productions that, during these two years, children make a dramatic increase in their ability to differentiate the weight of substances from the object's absolute weight. Similar conclusions were reached by Smith et al. (1985) in their density studies which indicated that 3-year-olds solved density problems by relying on weight as a critical factor but by the time they reached the ages of 5 to 7 years both weight and density were used in their predictions. By contrast, 8- and 9-year-olds generally used density.

This study of children's scientific reasoning ability made me acutely aware of the role of specialized knowledge in acquiring a complex concept such as buoyancy. When a concept has such a sizable knowledge component, it is to be expected that there will be a difference between age groups regarding the beliefs or naive theories they construct in their attempts to understand this physical phenomenon. One of the cognitive underpinnings that may be responsible for the construction of children's "common sense" mental models of scientific phenomena is a complex interactive process between children's perceptual and conceptual representations of everyday phenomena in their physical world. More importantly, understanding is an essential principle in and the driving force behind the construction of children's representational thought.

Strengths of the Study

From an empirical point of view, the results of the study were encouraging in that similar conclusions were reached regarding children's conceptual development of buoyancy in two different contexts: (1) an informal inductive method of inquiry and (2) a formal investigation using the methodological procedures of neo-Piagetian studies. The classroom-based teaching project provided a beginning to aiding the recognition of conceptual differences in children's understanding of buoyancy as they emerge in the context of active learning. The formal assessment was necessary to provide stronger empirical support for the theory by testing the developmental model's validity in a "hypothetico-deductive" manner. Its purpose was to eliminate the possibility of having simply "read in" such a sequence to match Case's theory. Moreover, the designing of such a buoyancy measure enabled me to predict the conditions under which children's performance would and would not be altered.

What distinguishes neo-Piagetian studies from other research inquiries is the presence of a common metric based on theoretical predictions which are used for classifying the developmental level of children's conceptual representations in terms of their complexity. This enables researchers to articulate the nature and development of children's understanding of a scientific concept at various points in their development. By contrast, the tasks designed to measure children's conceptual development in the modular (e.g., theory-based approach) and learning tradition did not have a precise metric to document changes that occurred at different points in a child's development. In these traditions, a general description of conceptual change was offered in terms of periodic minor and major restructurings of knowledge. For instance, utilizing a theory-based approach to cognitive development, Carey (1985) outlined four components of conceptual change: (1) representation of new relations among concepts, (2) creation of new schemata, (3) a different solution to old problems and (4) fundamental changes in core concepts. However, very few attempts were made to provide any fine-grained analysis of how such "explanatory mechanisms" can delineate the conceptual changes in children's "blueprints" of a specific concept (e.g., density). For the most part, the studies attempted to explain changes in more of an ad hoc way in that they were less formally documented than neo-Piagetian studies. From the present point of view, the important point to note is that since the concepts have not been scaled in terms of a common metric, the conclusions that one can draw from the findings of modular studies are limited. Whereas modular theorists tend to rely on case studies to describe and explain conceptual changes in children's mental models, neo-Piagetians use a developmental model (Case, 1985, 1992) in the form of a continuing framework that enables researchers to chart conceptual changes in children's understanding of a specific concept at various age levels.

Another strength of the present research inquiry is that both the general and specific aspects of children's developing epistemological understanding of buoyancy are articulated. Neo-Piagetian theorists have for years maintained that children's information-processing capacity increases with age and that this increase plays a strong role in facilitating and/or constraining the other more specific changes that take place in their cognitive systems, for instance, the development of children's conceptual representations (Case, 1978, 1985; Fischer, 1980; Halford, 1982, 1988; Pascual-Leone, 1970, 1987). A dominant theme within the neo-Piagetian framework is the claim that changes in the overall speed of children's information processing have a strong effect on the size of their working memory and that the size of their working memory in turn imposes a strong influence on the number of units or chunks of information that children can represent simultaneously. Therefore, the construct "working memory " may be considered as the workspace of thinking, an active cognitive process. It was this construct upon which the multilevel set of tasks were theoretically designed. The increasing task complexities were intended to correspond to the quantifying changes in the amount of information a child can process in parallel at different points in his or her development.

In recent years, Case (1992, 1996) shifted the locus of generality in children's performance from the size of their working memory (as measured by the number of units of information a child can hold in their memory while working on a problem) to a central conceptual structure that is assembled and nested within that memory. With respect to this study, a central scientific structure was developed and used to interpret the blueprints (i.e., general schema) of children's reasoning about buoyancy in terms of how children dimensionally represented this structure (i.e., in a unidimensional, bidimensional or integrated bidimensional fashion). Therefore, the general cognitive developmental differences in conceptions of buoyancy from 6 to 10 years were delineated through the representational complexity of this scientific structure that was reflected in children's responses on the tasks.

Processing capacity is not the only factor that affects children's conceptual development of physical concepts in the science curriculum. There are several factors that influence conceptual understanding of a more specific nature, many of which do not affect demand on the processing load per se. For instance, it was also important to take into consideration the limited scientific knowledge that children of this age possess in understanding such a complex concept as buoyancy. Moreover, the ability to generate hypotheses to support buoyancy judgments also influences how an individual is capable of developing a common sense understanding of such a complex concept.

Children tend to be novices in most domains and the knowledge of the novice is often limited to surface features until instructional support is provided. Metz (1995) documented a number of studies wherein elementary school children were capable of understanding and constructing abstract ideas about a scientific concept. For instance in the work of Smith, Carey and Wiser (1985), by the age of 8, many children were capable of deepening their understanding of weight by reconceptualizing it as a fundamental property of matter. These researchers concluded that "children now have principled generalizations that the weight of an object is a function of both the amount of and the kind of matter in the object" (p. 227). Similarly, the 10-year-olds in the current study used the same abstract understanding of weight (i.e., density) in their buoyancy explanations despite no formal instructional support. They were able to transcend the concrete and directly perceptible factors to achieve a deeper understanding of the notion that density matters most in buoyancy. A data analysis of the explanations offered by children after testing their buoyancy predictions revealed `that many children in each of the three age groups were capable of reflecting upon their theories and were even willing to provide an alternate explanation if the previous theory no longer seemed plausible. In either case, a significant improvement in their understanding of what determined an object's buoyancy was observed; some individual's level of reasoning advanced to the next substage of the model.

To conclude this section, a final reference needs to be made regarding the validity of the buoyancy measure. The different levels of dimensional thought from predimensional through to integrated bidimensional were clearly reflected in the incremental complexity of the tasks on the measure. Furthermore, the results also suggested that the structural level of children's reasoning accounted for more variability in the findings than task effects did despite the problems encountered on task item 3.1 (carrot vs parsnip) and 3.3 (sugar cube vs wood block). An analysis of the data revealed consistent levels of reasoning within each task and across all five tasks by each age group. Any variation in an individual's performance on the measure rarely exceeded one substage above or below his or her predicted level.

Limitations of the Study

There are three limitations to the study. The first is sample size (n = 60). The small population of 6-, 8-, and 10-year-olds who were administered the buoyancy task battery does not have enough statistical power to make the results generalizable to all elementary school children of these ages. However, the results of this developmental study are consistent with previous neo-Piagetian studies in terms of the distribution of prototypical thinking as well as the number of responses falling above and below the prototypical level for each age group. Only one 6-year-old child demonstrated advanced reasoning on the tasks equivalent to that of 8-year-old thought. By contrast, no 8- or 10-year-old participant scored above the predicted level. In addition, this sample's performance on the buoyancy measure followed the same general structural pattern of progression as that of the tests of scientific reasoning conducted by Marini (1992), including Siegler's (1978) Balance Beam and Shadows and Noelting's (1982) Juice Mixing Tasks. The same pattern of results was also observed on tests of different aspects of children's numerical understanding (Case & Sandieson, 1988; Case & Sowder, 1990; Griffin, Case & Sandieson, 1992; Grifin, Case, & Siegler, 1994).

Although the performance of the 10-year-old group was slightly lower than the theoretical expectation, the results in general suggest that the hypothesized prototypical knowledge components unique to each age level were empirically validated. As mentioned earlier, the processing demands of task 4 may have not have been a true reflection of 10-year-olds' developmental capacity but an index of their possible learning potential at this level of conceptual complexity. Case (1985, 1992) postulated that, at 10 years of age, children have a working memory capacity of four items or objectives but it may, in fact, be lower. He believed that the size of children's working memory exerts a strong influence on the size of the "goal stack" that children can maintain in active state and hence the complexity of problems they can solve. Task 4 on the buoyancy measure required integrated bidimensional thought to correctly solve each problem at this level. Case (1985, 1992) hypothesized that 10-year-olds were capable of achieving this level of reasoning which requires a working memory capacity of four "goal stacks". However, Dennis (1992) suggested from her studies that a slowdown of growth occurs in working memory capacity around the age of 10 years. In view of the underlying variable against which neo-Piagetian task analyses are gauged is working memory capacity, not age, her suggestion has implications for a revision of Case's theory.

Density is a very difficult abstract concept for children of this age level to articulate and while 10-year-olds may have the capability to conceptually understand the notion of relative weight between the object and the two mediums, they seemed unable to explain their understanding in explicit or conclusive terms. As a group, the 10-year-olds in this study demonstrated an ability to integrate their knowledge but the conceptual explanations they offered did not comply with the established criteria. This evidence suggests that 10-year-olds were not capable of understanding density at this level of complexity without some type of instructional support. An alternate possibility for why these older children were unable to achieve this conceptual level of understanding could be directly related to their lower working memory capacity around this point in development as suggested by Dennis (1992).

The second limitation is that task performance was based on children's ability to articulate their buoyancy predictions. Buoyancy is a very difficult concept to explain and of course requires some form of understanding of density. Unbeknownst to the interviewer, children may have intuitively or implicitly understood why a particular object floated but were unable to explain it in explicit terms. To ensure that the results did not simply reflect language competence as children matured rather than their level of understanding of buoyancy, "bare-bones" responses were accepted at any level as long as they complied with the scoring criteria for the postulated underlying structure. Furthermore, the use of probes during the interviews enabled children to clarify or restate what they conceptually understood. Verbal fluency, therefore, was not considered a contributing factor to the increase in complexity of older children's responses. This issue of language control and the concept of a "bare-bones" response (Griffin, 1992) was addressed in detail in Chapter 4. Surface differences, while important in qualitative analysis, were generally de-emphasized in the scoring criteria since the postulates of the theory are couched at the level of deep structure and general domain content. However, language may be a factor in judging children's responses and should be controlled in future studies.

The third limitation is that all sixty participants attended the same elementary school in which each age group was randomly selected from two classroom divisions. The use of one school restricts the possibility of generalizing the results to a broader population of students of similar ages. However, in the first phase of the study, children (n = 92) were selected across schools and districts in the Greater Vancouver area and these participants' data were used to build the structural model of children's understanding of buoyancy from the ages of 4 to 12 years. Thus, the study's results may generalize further. Replication is necessary to test generalizability.

In and of itself, the results of the study are of interest to science educators particularly in the area of teaching physical sciences. It is important for teachers to understand learning from the perspective of a learner and then design instruction accordingly based on that same perspective. This is instrumental in ensuring successful teaching-learning connections. Teachers need to know what their students are understanding. Understanding entails having a mental model that represents the structure of the concept or phenomenon. The next section considers the educational implications of how this study conducted within a neo-Piagetian framework is able to enhance teachers' understanding of the nature and development of children's scientific knowledge. A comparison will be made of the educational significance of this form of inquiry to the other three research directions reviewed in the literature : (1) cognitive development as theory development, (2) novice-expert learning theory and (3) social constructivism.

Educational Implications

Utilizing the concept of mental models, developmental theorists from each of the foregoing inquiries have provided educators with alternate ways for viewing the nature and development of children's conceptual understanding of scientific knowledge. The notion that children have mental models or conceptual representations of natural physical phenomena prompted investigators to view children's development as domain-, task- and context-specific. In earlier years, educators had questioned the utility of Piaget's notion of a general system of logical operations as a means of explaining how children acquire their knowledge of the world. The development of cognitive models provided researchers with a rigorous explanation of what it means to understand something (Case, 1992; Chapman, 1990; Fischer, 1980; Halford, 1993). The identification of prototypical mental models of children's scientific reasoning at different age levels provides a basis for the "optimal match" (Donaldson, 1979) between learner and curriculum.

Using the construct of mental models as a theoretical framework, these research inquiries set out to address two very important questions relating to children's development of scientific reasoning and knowledge. First, **what** does children's conceptual understanding of a specific concept look like at various points along a time continuum (the description question) ? Second, **how** do changes in children's representational thinking come about (the explanation question) ? In response to the research questions, each method of inquiry adopted a specific focus or dimension of children's representational thinking in a specific area of science. For instance, Carey and her colleagues (1985, 1991) have examined the theory-like nature of children's conceptual representations of physical matter. Interpreting children's mental models within a "naive theories" framework may place too much emphasis on the theory-like nature of children's informal ideas.

Halford (1993) proposed that the mental models that influence cognitive development are probably less explicit and less accessible to consciousness than scientific theories. He claimed that it is debatable whether young children have developed theory-like conceptual structures as posited by Carey (1985). The nature of children's responses to the set of buoyancy problems in this study supports Halford's argument. Children's reasoning about buoyancy appeared to represent a collection of simple beliefs based on causal relations among single variables. In fact, these simple beliefs, often contradictory, appeared to reflect what diSessa (1988) articulated as "a fragmented collection of loosely connected ideas" (p. 55). There was no notion that beliefs themselves were organized into intuitive theories or "interpretive frameworks" at this point in a child's development. In the context of the novice-expert inquiry, the difference between novice and expert content knowledge is that an expert's is well-organized whereas a novices' is more disconnected which often leads to inconsistent theories within children's conceptual systems leaving children to cope with paradoxes within their own knowledge. Thus, novice knowledge appears to exhibit some of the fragmentation typical of naive scientific knowledge as hypothesized by diSessa (1988).

In terms of educational significance, the novice-expert method of inquiry has provided educators with a more detailed analysis of children's mental models in the science domain than the theory theory direction (Carey, 1985; Larkin, 1983). Empirical data from the theory-based approach to cognitive development have been generally more descriptive than explanatory in their account of the development of children's scientific knowledge. In contrast, the data from novice expert studies not only delineate differences in the novice and expert conceptual systems but also provide a process explanation for the developmental changes in the semantic and syntactical networks of children's conceptual representations of physical concepts (Pozo & Carretero, 1992). The intention was to provide educators with both a descriptive and explanatory analysis of how learning evolves from the perspective of the learner and hence avoid the current problem of the mismatch between a learner's conceptual level of understanding and instructional methods.

What distinguishes neo-Piagetian research from other methods of inquiry is that studies are conducted within a continuing framework in the form of a developmental model based on age-level postulates (Case, 1992) which enables researchers to recapitulate the developmental sequence of children's conceptual representations of a specific concept from early childhood to late adolescence. The notion of a *central conceptual structure* (Case, 1992, 1996) provides not only a structural foundation upon which to build specific "blueprints" of children's general schema of "naive theories" about a specific concept but also provides a common metric to assess the complexity of children's representations at a fine grain of analysis. To recap briefly, *central conceptual structures a*re defined as forming the basis of a wide range of specific concepts in a domain (*central*), as consisting of the meanings or concepts assigned by the child to his/her world (*conceptual*), and as constituting children's internal mental entities, or mental blueprints (*structures*). The revision of children's "theories" over the course of development are articulated by (1) the gradual increase in the structural complexity of this central conceptual structure and (2) the changing conceptual representations that are nested within these structural changes. In essence, Case's developmental model enables researchers to articulate the structural and conceptual nature of children's mental models at various points in their development. Investigations using the "naive theory" notion of cognitive development mainly focused on conceptual changes (Carey & Smith, 1993; Kohn, 1993; Smith, Carey & Wiser, 1985) while contemporary research in the novice-expert approach to cognitive development essentially analyzed the structural reorganizations in children's and adult's knowledge networks (Chi & Rees, 1983; Pozo & Carretero, 1992).

From a neo-Piagetian viewpoint, age is considered to be the general factor related to cognitive development as it pertains to the gradual changes in a child's processing efficiency that occurs with maturation. Case (1985, 1992) and Olson (1989) postulate that this increasing capacity, in terms of processing efficiency, can serve to explain the development of children's representational abilities. On the other hand, novice-expert theorists agreed with modular theorists in suggesting that one of the most important contributing factors that induced change in children's development was the change that took place in the structure of their conceptual knowledge. The results of studies conducted within the novice-expert framework revealed that cognitive development was related more to gaining expertise in a particular area through experience and the accumulation of specialized knowledge than to age. Theorists in this field of study argued that a child or adult may function at a higher level in one content area than in another if he or she has acquired expertise in that area through extensive practice and experience (e.g., Chi & Glaser, 1988). In addition, as children acquire more experience in a specific area they begin to form a more sophisticated conceptual system which in turn leads to more efficient problem-solving strategies.

In the context of the neo-Piagetian framework, researchers are able to consider both the general and specific mechanisms of cognitive development as both perspectives are nested within the construct of a *central conceptual structure* (Case, 1992, 1996). This enables developmentalists to investigate how children's processing limitations constrain and facilitate the mental model of knowledge representations a child can enact at any given age. In so doing, a more complete picture of children's conceptual development of a specific concept can be assembled. Therefore, neo-Piagetian theory has educational relevance to the teaching of science by combining a concern for children's general development with a concern for the teaching of specific subject matter (e.g., buoyancy).

Developmental constraints on children's scientific reasoning have important implications for improving science instruction. It is important to take into account children's information processing limitations at different points in their development when planning science units and complex concepts such as buoyancy or density. Case (1985, 1992) believes it is possible to circumvent the working memory demands of a complex concept (e.g., buoyancy), by providing an age-appropriate representation to serve as a guide such as a mnemonic aid. This would be in the nature of a type of instructional device, which in Caseian terms is called "conceptual bridging" (Case, Sandieson & Dennis, 1986). The purpose of this technique is to reconceptualize the advanced structure in such a way that it corresponds with the child's existing mental model and secondly that the complexity and working memory demand of the task be minimized. Furthermore, representational and working memory support should be provided during instruction and independent practice until the new advanced structure has been consolidated.

"Conceptual bridging" would appear to be an appropriate technique in the teaching of physical science especially when one considers the complexity and abstract nature of such concepts. This procedure not only provides perceptual cues but also provides conceptual support by means of representing the task or concept in a way that will take account of a child's existing level of conceptualization while guiding them to higher levels of understanding. In other words, instruction should fit well with a child's existing conceptual structure by making minimal demands on the child's working memory. This instructional methodology has now been used to develop programs in a number of areas, including math (Case & Griffin, 1990), story composition (McKeough, 1992) and several life skills such as telling time (Case, Sandieson & Dennis, 1986) and making change with money (Sandieson & Case, 1987). However, its potential use for promoting conceptual understanding of scientific phenomena has yet to be examined.

Future Research

Understanding the developmental progression of a scientific concept such as buoyancy will facilitate instruction in the teaching of such a complex concept. Knowing where children are in their scientific understanding and where they could progress allows for the building of "conceptual bridges" (McKeough, 1992) to higher levels of reasoning. An interesting follow-up to this project would be to conduct an instructional study to assess the effects of a developmental approach to advancing children's conceptual understanding of buoyancy. For example, utilizing a procedure that is designed to build a "conceptual bridge" between children's current level of thinking and the next in Case's (1985, 1992) developmental hierarchy, an attempt could be made to promote 8-year-olds' conceptual understanding of buoyancy. Eight-year-olds could be taught to construct a more advanced form of reasoning, specifically, integrated bidimensional thought which is characteristic of 10-year-old's ability in Case's model. This new level of thought would not only involve the differentiation and coordination of relevant factors that determine an object's buoyancy but it would also help children begin to integrate such factors in a more sophisticated fashion. In operational terms, this would include the teaching of volume and providing guided assistance in developing compensation strategies between the properties of object and medium.

It is important for teachers to take into account children's processing limitations at different stages in their development as well as their limited knowledge representations of complex physical concepts when planning instruction. A technique such as "conceptual bridging" provides the potential of combining both these considerations and could perhaps enable children to reach higher levels of conceptualization previously assumed impossible. Furthermore, a richer conceptual framework for elementary science instruction may be developed if this neo-Piagetian instructional methodology was incorporated into the generative teaching model currently used by social constructivist researchers (Bloom, 1995; Woodruff & Meyer, 1995). In this teaching model, children work in small groups as "collaborative cohorts" in a consensus-building process about a specific concept or problem. Their main goal is to reach a group explanation for and a mutual understanding of the topic under investigation.

In summary, within the neo-Piagetian tradition, Case (1985, 1992) has designed both a developmental and instructional model that has several practical implications for science educators. First, the developmental model enables educational researchers to conduct a detailed analysis of the structural and conceptual changes that occur in children's representation of scientific knowledge at various points in their development. In so doing it is now possible for educators to (1) assess children's "entering competence" in a concept (e.g., buoyancy) and (2) set developmentally realistic goals for instructional programming. Second, the instructional model enables teachers to design a curriculum that recapitulates the developmental sequence of children's conceptual representations of a specific concept. It recommends a "conceptual bridging" strategy that should (1) fit well with the child's existing conceptual representation, (2) permit the teacher to introduce a higher level of conceptualization and (3) make minimal demands on the child's working memory. More specifically, the purpose of this technique is to circumvent children's processing capacity limitations by linking the child's current level of understanding to the next level in the developmental sequence of the domain in question.

In contrast, the novice-expert theorists emphasized the teaching of specific content knowledge in terms of the underlying conceptual knowledge representations required to interpret and apply a physical concept (e.g., mechanics) accurately and efficiently. Although their research provided educators with valuable information regarding processes underlying structural reorganizations in both children's and adults' knowledge networks (Chi & Rees, 1983; Pozo & Carretero, 1992), what was lacking was any attempt to explain the general mechanisms of cognitive development that induced such conceptual changes in their knowledge representations. Interestingly, their emphasis on content is substantiated by evidence suggesting that once knowledge of a specific domain is mastered, experts display a sophisticated use of effective problem-solving strategies (e.g., Chi, 1988). These theorists also maintain that without the necessary domain-specific knowledge, general strategies have minimal effect on enhancing task performance in most cases (e.g., Pozo & Carretero, 1992).

The difference in the neo-Piagetian instructional approach from this learning theory tradition is that the main focus of instructional planning is on constructing ways to circumvent children's limited conceptual representations so that a more advanced conceptual understanding can be achieved. In order to accomplish this goal, instruction from a neo-Piagetian viewpoint follows the developmental progression of children's understanding of a scientific concept. As a result developmental theory plays a more critical role in determining the nature of the curriculum than the novice-expert learning theory. In conclusion, neo-Piagetian research connects the fields of cognitive developmental theory and instructional practice more efficiently than other approaches by tuning instruction more closely to children's underlying cognitive structures.

Conclusion

From an educational perspective, valuable information is gained often from a critical analysis of the data collected from children's responses to a particular topic. The type of content and the patterns of thought that are generated by children provide insight into how children intuitively approach a problem or construct a conceptual understanding. In addition, the content and patterns of children's thought can provide teachers with insight into the next level of conceptualization and their developmental instruction can be planned accordingly. Most science instruction is often insensitive to students' common sense understanding of a concept under study and as a result there appears to be an increasing separation between children's intuitive, informal understanding of scientific phenomena and the formal mathematical conceptualization which often results in a lack of understanding.

One of the challenges that science educators face in the teaching of physical sciences is how to maintain a happy "marriage of mutual understanding" between children's common sense understanding and formal scientific knowledge. Children's common sense understandings are strongly supported by personal experience and social interaction. Similar patterns of thinking in children's conceptual understandings are partly a result of shared ideas and sense-making conversations with peers during inquiry activities in science lessons (Arlin, 1990; Driver, 1994; Pea, 1993). Shared ideas constitute socially constructed "common sense" ways of describing and explaining physical phenomena and strongly influence children's individual personal constructions.

From a different educational perspective, one of the cognitive underpinnings that may also be responsible for the construction of children's "common sense" mental models of scientific phenomena is a complex interactive process between children's perceptual and conceptual representations of everyday phenomena in their physical world. More importantly understanding is an essential principle in and the driving force behind the construction of children's representational thought. It is the responsibility of educators to attempt to make invisible phenomena (e.g., density) "visible" for children to achieve a deeper understanding of a concept. Driver (1985) postulates that children learn to wear "conceptual spectacles" which involves constructing mental models for such abstract concepts which are not perceived directly such as light, electricity or particulate matter.

Based on the results of this study, teachers need to be aware that conceptual change, particularly in the physical sciences is a gradual process requiring opportunities for children to experiment with their thinking, test hypotheses, and confirm and disconfirm beliefs. In this process, teachers need to attend to children's struggles to acquire concepts and guide them in appropriate directions (Watson & Konicek, 1990). If the goal of teaching is to support children's learning, "We should do well to try and understand what children's learning is like, what the child is trying to do" (Lindfors, 1984, p.605). Although educators have gained some understanding of the effects of cognitive development on scientific reasoning, most science instruction still lacks theoretical foundations based on developmental research. The contributions of Case's (1985, 1992) neo-Piagetian model of cognitive development to advancing educational theory and practice in the field of physical sciences are particularly promising.

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APPENDIX A

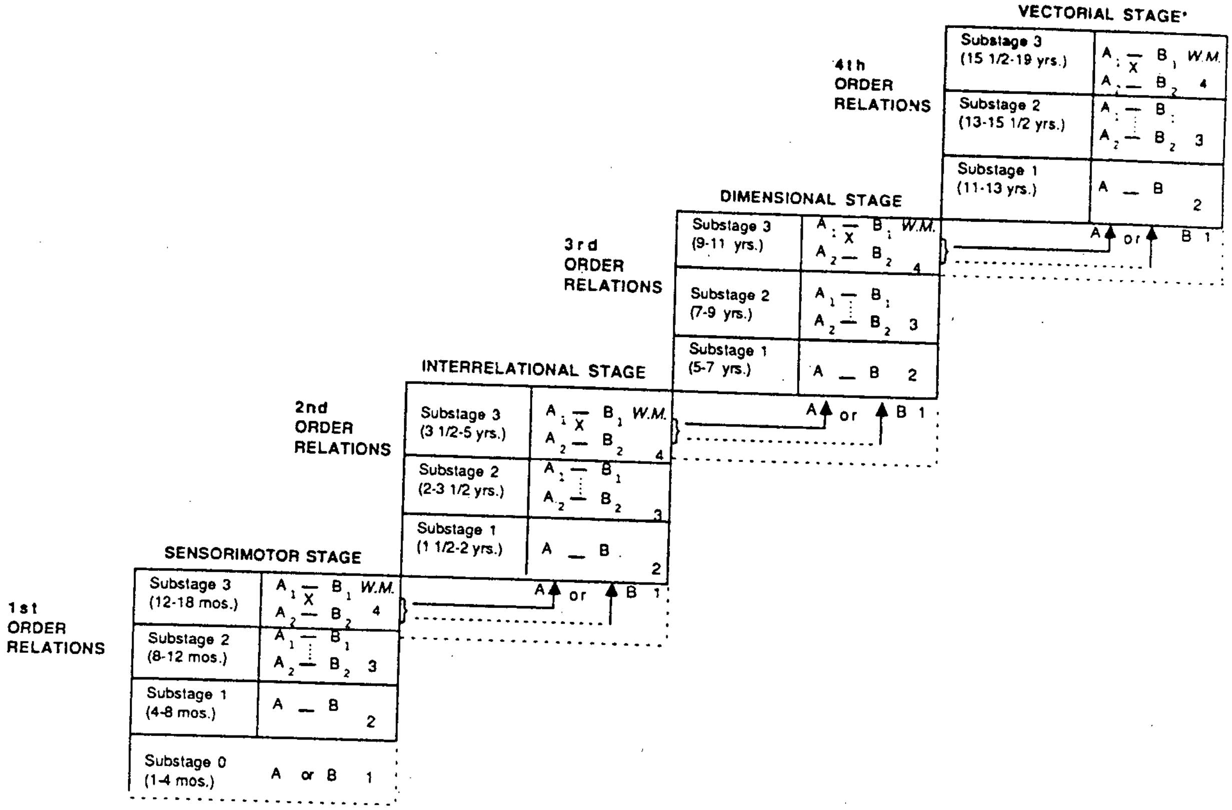

Figure1. General stages and substages in children's cognitive development, as described in Case (1985). The structural diagrams indicate the way in which existing control structures (represented in letters) are used as elements in the construction of higher-order control structures. In the transition from substage 0 to substage 1 (bottom left), a new control structure is formed from two previously separate control structures A and B. The new structure is symbolized as A-B. In the transition from substage 1 to substage 2, two control structures of the new sort (A1-B1 and A2 -B2) are differentiated and then integrated with each other. In the transition from substage 2 to substage 3, no new units are added, but the integration becomes more solid than the previous substage. Finally, in the transition to the next major stage, each one of these elaborated units is treated as a single element, and the entire process recycles. Beside each structural form,the characteristic working memory demand (noted W.M.) is given; as may be seen, this progresses from 2 to 4 within each stage.

From: Case, R., & Okamoto, Y. (1996). The Role of Central Conceptual Structures in the Development of Children's Thought. Monographs of the Society for Research in Child Development 61,Ser. No. 246, pp.201.

APPENDIX B

Letter to Parents Requesting Interview

Dear Parent or Guardian,

Over the past four years I have been working on my doctoral degree at the University of British Columbia (UBC). The research for my degree is based on children's learning of scientific concepts at different age levels. I am particularly interested in what children know about the concept of buoyancy, how they know whether an object will float or sink. I am writing to request your permission for your son or daughter to participate in my research project entitled "Children's Understanding of Scientific Concepts." The purpose of this study is to investigate the nature of children's understanding of buoyancy at the ages of 6, 8 and 10 years so that we as teachers may gain more insights into the learning of science from the child's point of view at the elementary school level. Such information will prove useful to teachers in planning instruction that not only enables children to have a better understanding of such difficult concepts but will also better prepare them for High School Science.

Students who participate in this research project will be presented with 5 tasks involving objects of different sizes, shapes and weights. The students will be interviewed about the buoyancy of these objects. First, they will be asked to make a prediction as to whether the object will float or sink in water and will then be asked to explain why they think it will float or sink. Following this, students test their predictions by putting the object in the water and whenever, a prediction proves incorrect students will be asked to suggest a reason for this unexpected outcome.

Your child was selected randomly from a list of 6-, 8-and 10-year-olds in the school. I would like to work with your child individually for approximately 20 minutes. The interview will be conducted at Belmont School in a vacant room set aside for this project. Responses will be tape-recorded so that they can be transcribed later. All information collected will be strictly confidential. To ensure confidentiality, no identifying information will be recorded and all of the data will be coded by number. In consultation with your child's teacher, an appropriate time will be arranged to conduct the interview so that it will not unduly interfere with your child's classroom schedule.

Your child's participation in the project is entirely voluntary and withdrawl from the research study or refusal to participate will not influence your child's class standing in any way. Children whose parents do not consent to their participation in this project will continue their daily classroom schedule as usual.

I would be very pleased if your son or daughter does decide to participate if you are willing to give him or her permission to do so. Please indicate on the Parent Consent Form provided on the attached page whether or not your son/daughter has permission to participate in this science project. Would you then kindly sign and date the form and return it to your child's teacher. Please keep the first page of this letter for your own records. Should you have any questions, please feel free to call me or Mr. McManus, the principal, at the school at 533-3641. In addition, you may also contact my faculty advisor Dr. Marion Porath who would be pleased to discuss my study with you. She can be reached at UBC at 822-6045. If you have any concerns about your child's treatment or rights as a research subject you may contact the Director of Research Services at the University of British Columbia, Dr. Richard Spratley at 822-8598. Thank you very much for your cooperation.

Sincerely,

Gillian Bickerton

PARENT CONSENT FORM

Study Title: Children's Understanding of Scientific Concepts

Principal Investigator : Dr. Marion Porath, Associate Professor,
Department of Educational Psychology and
Special Education,
University of British Columbia,
2125, Main Mall,
Vancouver, B.C. V6T 1Z4

Co-investigator: Gillian Bickerton, Graduate Student, Department of Educational Psychology and Special Education, University of British Columbia.

(Detach here and return to school)

I have read the attached letter regarding the study entitled " Children's Understanding of Scientific Concepts."

______ Yes, my son/daughter has my permission to participate.

______ No, my son/daughter does not have my permission to participate.

Parent's Signature________________________________

Son or Daughter's Name____________________________

Date _______________

APPENDIX C

STATEMENT SEEKING VERBAL ASSENT FROM THE STUDENTS

The interviewer:

"I'm interested in how children learn about things in science and especially what they know about floating and sinking. I want to find out what children your age can tell me about why some things float in water and other liquids while other things sink. I am writing a book and would like to use your ideas to help me understand what children your age know about floating and sinking. I am inviting you to participate in this research project in which you will have the opportunity to work like a scientist doing some experiments to see whether objects float or sink. But before you decide whether or not you want to participate, I will first tell you about the kind of things you will be asked to do. You will be given different sorts of objects to look at closely and will be asked to decide whether or not each object will float or sink in water or some other liquid. After you have made a choice, I will ask you to tell me why you think that object will float or sink. I will tape-record your ideas as it would take too long to write them down during the interview. As soon as you have shared your ideas with me, you will be able to put the object in the water and see for yourself whether it floats or sinks. **This is not a test.** It is exactly what scientists do. They like to test out their ideas. I am more interested in what you think makes the object float or sink than whether you make the right decision. I hope you are interested in working with me on this project and take this opportunity of being a scientist, but if you don't want to participate that is all right too."

APPENDIX D

STUDENT INTERVIEW PROTOCOL

Subject #: **Date:**

Task #1: Predicting buoyancy based on one variable
Question : Will this fools gold (cork, soap, plastic ball) float? Why do you think so?

1. fool's gold **Response :** sink/float
Explanation:

2. cork **Response :** sink/float
Explanation:

3. soap **Response :** sink/float
Explanation:

4. ball **Response :** sink/float
Explanation:

Task #2 : Predicting buoyancy based on coordinating two factors
(constants: weight/size; variable:shape)
Question : Which of these two objects will float? Why do you think so?

1. potato/porcelain bowl **Response:** potato/bowl
Explanation:

2. metal hat lid/coin **Response:** lid/coin
Explanation:

3. foil ball/boat-shaped **Response:** boat-shape/ball-shape
Explanation:

What will happen ? Will these objects float or sink?
(constants: density, size, weight; variable: shape)
4. cylinder/pyramid **Response:** sink/float
Explanation:

<u>Task #3 : Testing for the effects of an object's material</u>
(constants: weight,shape;variables:size/density)
Question : Which of these two objects will float? Why do you think so?
1. carrot / parsnip **Response :**carrot/parsnip
Explanation:

2. orange/ beet **Response:** orange/beet
Explanation:

(constant:shape; variable size/weight
3. cube/wooden square **Response :** sugar cube/wood
<u>Explanation:</u>

4. Tennis ball/marble **Response:** Ball/marble
<u>Explanation:</u>

Task #4: **Testing two object's buoyancy in different liquids**

1. Will this **egg** float in **water** or **salt water**? **Response:** water / salt water

Explanation:

2. Will this **grape** float in **water** or **salt water**? **Response:** water/salt water

Explanation :

3. Will the **rosewood** float in water or salt water? **Response:** water/salt water

Explanation :

4. Will the **lime** float in water or salt water? **Response:** water/salt water

Explanation:

Task #5: Understanding relative density of object and medium

Children are presented with two sets of two different objects of varying densities and two containers of different liquids. Their task is to decide which object floats in each liquid. Subjects are informed that oneof the objects will float in both liquids while the other object floats in one.

1. cranberry in oil/ salt water

2. blueberry in oil/salt water

Explanation:
Why does the cranberry float in __________

Why does the blueberry float in ____________

3. Rubber duck in salt water/molasses

4. kiwi fruit in salt water/molasses

Explanation:
Why does the rubber duck float in ________

Why does the kiwi float in ________

APPENDIX E

A Description of the Buoyancy Tasks and the level of dimensional reasoning required

Task #1 - Level 0 Reasoning (Predimensional)

Task 1 represents the basal level on this buoyancy scale. Children were presented with four different objects one at a time. They were asked : Will this fool's gold (cork, soap, plastic ball) float in the water ? Why do you think so? Besides establishing a basal level for this Buoyancy Scale, this task also provided children with the opportunity to activate their thinking regarding the different factors that determine an object's buoyancy (e.g., weight, shape, substance, size). All the above factors were treated as variables for possible consideration. Children needed to demonstrate **predimensional** reasoning in their explanations. That is, they were required to identify <u>one</u> factor that determined an object's buoyancy. Most children consider weight as the critical factor in determining an object's buoyancy. In accordance with the theory, a buoyancy judgment based on <u>one</u> critical factor, such as weight, is defined as **predimensional** reasoning.

Criterion for passing each item = correct buoyancy prediction based on one factor

Criterion for passing Task 1 = 3 out of the 4 items must be passed

Task # 2 - Level 1 Reasoning (Unidimensional)

The purpose of this second task was to test for the effects of shape on an object's buoyancy. The weight of the following paired objects were held constant while shape, size, and density varied. In item #4 shape was the only variable; weight, size/volume and density were held constant. Since both objects were of equal weight, children needed to consider another critical factor to determine which of the two objects would float. Children were presented with the following pairs of objects, one pair at a time. They were told that only one of the objects floated.

Items #1 - potato and porcelain oval bowl

Items#2 - metal hat and coin (Mexican peso)

Item#3 - ball of foil and foil in a boat shape (equal amount of tinfoil)

Item#4 - wooden solids (cylinder and pyramid)

For items #1 to #3, children were asked: Which of these two objects will float? Why do you think so? For item #4, each student was informed that the wooden objects would either both float or both sink. Children were asked: Will these two objects float ? Why do you think so?

Children were required to demonstrate **unidimensional** reasoning in their explanations for which of the two objects floated. Unidimensional reasoning requires the coordination of two variables. Shape attributes were anticipated to be the most common variables in children's explanations for what determined an object's buoyancy. Acceptable responses were the coordination of two different factors (e.g., weight and shape; weight and substance; substance and size). Alternately, if two shape attributes were considered that also was accepted as unidimensional thinking. Any coordination of two variables represents one dimensional structure in children's thinking.

Criterion for passing each item = correct buoyancy prediction based on the coordination of two factors (one dimension varied)

Criterion for passing Task 2 = 3 out of the 4 items must be passed

Task #3 - Level 2 Reasoning (Bidimensional)

The purpose of this third task was to specifically test for the effects of substance and size on an object's buoyancy. Children were presented one at a time with the following four critical pairs of objects that pitted the properties of substance weight and density against each other. The questions were the same as those asked in Task #2.

Critical Pair #1 : carrot and parsnip

Critical Pair #2 : orange and beet

Weight and shape were held constant while size, substance and density varied.

Critical Pair #3 : sugar cube and wooden block

Critical #4 : tennis ball and marble

Shape was held constant while size, substance, weight and density varied

Children were required to demonstrate **bidimensional** reasoning in their explanations for which of the two objects floated. Bidimensional reasoning is characterized by the coordination of three variables, weight being considered the most critical of the three variables. Specifically, two different variables needed to be pitted against an object's weight to determine buoyancy. With each paired object, it was hypothesized that a comparison of substances would be made and then related to each object's weight. This pattern of thinking qualifies as one dimensional structure. Children needed to construct a second dimensional structure to demonstrate bidimensional reasoning. A second variable should be brought to bear upon the critical variable of weight. For instance, a size comparison of the paired objects might also be related to their weight. Alternately, bidimensional reasoning may be represented by considering how an object's weight is affected by two different substance properties .

Criterion for passing = correct buoyancy prediction based on the coordination of three factors (two dimensions varied)

Criterion for passing Task 3 = 3 out of the 4 items must be passed

Task #4 - Level 3 Reasoning (Integrated Bidimensional)

The purpose of this fourth task was to test an object's buoyancy in two different liquids. In order to do this, children needed to make a direct relationship between the object and the media. When predicting buoyancy children needed to contrast an object's weight to the weight of the media (different liquids).

Children were presented with two identical containers of equal amounts of liquids. One container held ordinary water and the other held salt water. Children were clearly able to visibly differentiate between the two liquids. Four different objects were then given to them one at a time. Children were asked : Will this egg (grape, rosewood, lime) float in water or salt water ? Why do you think so? In these tasks, objects remained constant but the liquid media varied.

To qualify as integrated bidimensional reasoning, children were required to contrast the properties of the object and liquids in a more integrated manner. Like the previous level, two coordinated dimensional structures are present but the relationship between variables affecting the object's density is more elaborately related to the properties of the liquids in terms of their density. Children needed to demonstrate compensation between variables by differentiating between the properties of object and liquids.

Criterion for passing = correct buoyancy prediction based on compensation between object and medium (different liquids)

Criterion for passing Task 4 = 3 out of the 4 items must be passed

Task #5 - Level 4 Reasoning (Vectorial Stage)

The purpose of this task was to establish a ceiling level in children's understanding of buoyancy. The required level of reasoning for this task corresponded to a new stage in Case's developmental model. It was designed to assess an abstract understanding of relative density of object and medium. Children were presented with two sets of two different objects of varying density and two containers of different liquid densities. Children were told that one of the objects would float on both liquids while the other object floated on one. They were asked to predict which of two objects would float on both liquids and to justify their predictions.

Critical Pairs #1 : cranberry/blueberry; oil/salt water

Critical Pairs #2 : rubber duck/kiwi ; salt water/molasses

With these two tasks all critical factors that determine buoyancy are treated as variables.

Acceptable responses for this task required children to demonstrate an understanding of proportional reasoning (i.e., density as mass per unit of volume) when comparing object and liquid densities. It was hypothesized that the majority of participants would fail this buoyancy problem with the possible exception of a few 10-year-olds who were able to explain buoyancy in more abstract terms by way of differentiating between the variables of weight, volume and density of both object and media.

Criterion for passing = correct buoyancy prediction based on a comparison of object and liquid densities in terms of proportional reasoning.

Criterion for passing Task 5 = 3 out of the 4 items must be passed

APPENDIX F

SCORING CRITERIA

Score 0	one factor	Examples: heavy or light (weight) big or small (size) round (shape)
Score 1	two factors	Examples: weight + shape (material, texture, size) 2 shape attributes
Score 1.5	three factors or two factors integrated (weight + size)	Examples: weight + shape + air (not explained) or "light/heavy for its size."
Score 2	three factors	Examples: weight + substance + air inside **or** weight + substance+ size
Score 2.5	three factors	Examples: weight + 2 substance properties **or** weight + substance + size (substance properties explained in more detail - particles, molecules, compacted together)
Score 3	three factors integrated	Example: Compensation between weight (substance) of object & liquid or comparison of liquid substances + weight of object in relation to <u>one</u> liquid (Task 4 & 5)
Score 4	two abstract factors	Example: relative density of object & liquid Comparison of equal volume of object vs liquid density = weight per unit of volume proportional reasoning

APPENDIX G

CRITICAL BUOYANCY FACTORS USED IN EXPLANATIONS

1. Weight - heavy/light

2. Shape attributes - boat-shapes, round, curved, sides

3. Substance - texture (soft = light stuff; hard, squishy = heavy stuff)

4. Weight referring to heavy or light materials (e.g., plastic, rock, soap, wood)

5. Presence of absence of air in shape or substance

6. Size - big/small

7. Weight distribution of objects

8. Volume - water displacement

9. Relative weight - Relationship between object's weight to the weight of the water

10. Relative density - Relationship between object's density to the density of the liquid

Understanding of proportional reasoning: weight per unit of volume

11. Pressure - Upward force of water; downward force of object; buoyancy offsets gravity