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Mental Models of the Earth: A Study of Conceptual Change in Childhood

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This paper presents the results of an experiment which investigated elementary school children's conceptual knowledge about the earth. First-, 3rd-, and 5th-grade children were asked a series of questions about the shape of the earth. Children's responses to these questions revealed considerable apparent inconsistency. For example, many children said that the earth is round but also stated that it has an end or edge from which people could fall. A great deal of this apparent inconsistency could be explained by assuming that the children used, in a consistent fashion, a mental model of the earth other than the spherical earth model. Five alternative mental models of the earth were identified: the rectangular earth, the disc earth, the dual earth, the hollow sphere, and the flattened sphere. It is argued that these models are constrained by certain presuppositions which children form based on interpretations of their everyday experience. Some of these models (the rectangular earth and the disc earth) seem to be initial models children construct before they are exposed to the culturally accepted information that the earth is a sphere. In the process of knowledge acquisition, children appear to modify their initial models to make them more consistent with the culturally accepted model by gradually reinterpreting their presuppositions. Synthetic models (such as the hollow sphere and the flattened sphere) are generated by children

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as a solution to the problems arising from the inconsistency between their initial model of a flat earth and the culturally accepted, scientific model of a spherical earth. Children come to understand that the earth is a sphere only when the presuppositions that gave rise to their initial models have been reinterpreted.

The purpose of this paper is to investigate the development of children's conceptual knowledge about the earth's shape. We are interested in understanding the nature of children's initial knowledge about the shape of the earth and in finding out how this knowledge changes during the elementary school years as children are exposed to the culturally accepted information that the earth is a sphere.

Children and Adults Construct an Intuitive Understanding of the World

Research in cognitive science, science education, and developmental psychology during the last decade has shown that children and adults construct an intuitive understanding of the world which is based on their everyday experience. Although different terms have been used to refer to this type of knowledge—such as preconceptions (Ausbel, 1968), misconceptions (Novak, 1987), alternative frameworks (Driver & Easley, 1978), mental models (Collins & Gentner, 1987; White & Frederiksen, 1986), folk theories (Kempton, 1987), and intuitive theories (McCloskey & Kargon, 1988)—there is general agreement that this intuitive knowledge provides explanations of natural phenomena which are frequently different from the currently accepted scientific explanations and which tend to be resistant to change.

For example, Kempton (1987) argues that many adults use a folk theory in dealing with home heating thermostats. These individuals hold a "valve theory" and appear to believe that the thermostat controls the rate of heat flow just as an automobile gas pedal controls the amount of gas that is fed into the engine. Thus they think that the higher a thermostat is set the more heat will flow and the faster a house will heat.

In the domain of light many individuals believe that their eyes perceive objects directly and that color is a property of the objects themselves (Anderson & Smith, 1986). In addition, it appears that young children believe that the currently perceived color is a property of the object itself, even when they have seen the experimenter change the object's apparent color with a color filter (e.g., Flavell, Green, & Flavell, 1986). Some novices in the area of electricity believe that a switch is like the trigger of a gun; it sends an impulse to a battery to trigger current flow from the battery to a light bulb (Collins & Stevens, 1984). Finally, in the area of mechanics, many students, even after studying high school or university physics, do not understand Newtonian principles of motion, but interpret

motion phenomena using principles which are closer to everyday experience (diSessa, 1982; White, 1983).

Naive Theories versus Fragmented Knowledge

Some researchers believe that children's intuitive knowledge can be conceptualized as consisting of a coherent and systematic set of ideas which deserve to be called a theory (e.g., Brewer & Samarapungavan, 1991; Carey, 1985; McCloskey, 1983; Wellman, 1990; Wiser & Carey, 1983). In some cases the ideas of novices are found to resemble earlier theories in the history of science. For example, Clement (1982) and McCloskey (1983) argue that in the domain of mechanics many adults hold a systematic conception of motion which bears a striking resemblance to a pre-Newtonian theory known as impetus theory.

Other researchers think that naive physics consists of a fragmented collection of ideas which do not have the systematicity that is typically attributed to a scientific theory (e.g., diSessa, 1983, 1988; Solomon, 1983). According to diSessa (1988), naive physics consists of certain phenomenological principles, which are simple abstractions of everyday experiences. These phenomenological principles are, however, fragmented and shallow. Their fragmentation becomes apparent when children give different responses to questions which are fundamentally similar from the point of view of a physicist but differ in superficial characteristics (e.g., are phrased in different ways or are presented in slightly different contexts).

The Process of Knowledge Acquisition

Depending on how intuitive knowledge is conceptualized, different implications about the knowledge acquisition process can be drawn (see Vosniadou, 1991b). Researchers who view children's knowledge as fragmented and nonsystematic see the process of knowledge acquisition mainly as a process of collecting and unifying these knowledge fragments into consistent wholes (diSessa, 1988). Researchers who think that intuitive knowledge has the status of a theory see the process of knowledge acquisition in the context of theory change.

There are several distinct views on how theory change can occur during knowledge acquisition (see Vosniadou, 1989, and Vosniadou & Brewer, 1987, for a discussion of this issue). According to Keil (1979, 1983, 1986), children's initial theories consist of some skeletal but principled distinctions at the ontological level. Ontological knowledge becomes more differentiated and hierarchically integrated as children become older (see also Gelman, 1990). Similar approaches to the problem of theory change in terms of the increasing differentiation and hierarchical integration of

existing structures are common in the expert/novice literature (e.g., Chi, Feltovich, & Glaser, 1981; Larkin, 1981).

Carey (1985, 1986) has called this type of theory change "weak restructuring" to distinguish it from a different kind of theory change which she calls "radical restructuring." As an example of radical restructuring, Carey (1986) suggests that children might start with two theories (e.g., an intuitive physics embodying physical causality and an intuitive psychology embodying intentional causality) from which new theories emerge, in ways analogous to radical theory change in the history of science (e.g., Hanson, 1958; Kuhn, 1970, 1977).

Unresolved Issues

Many questions remain unanswered about the exact nature of intuitive understanding and about the knowledge acquisition process. First, it is not clear whether children's intuitive knowledge can be best characterized as fragmented knowledge or in terms of internally consistent naive theories. Although there seems to be converging evidence that individuals form certain principled distinctions which are based on their everyday experience (Nerssesian & Resnick, 1989; Vosniadou, 1989, 1991a; Vosniadou & Ortony, 1989), it must still be shown that they are capable of applying and coordinating these distinctions in a consistent and systematic way. Even if we assume that intuitive knowledge has the status of a theory, it is not clear how these theories change in the course of knowledge acquisition. In order to answer these questions, we need detailed descriptions of the knowledge acquisition process in a number of specific knowledge domains.

The Domain of Observational Astronomy

The present study was undertaken in the context of a larger project which investigated the process of knowledge acquisition in astronomy. Observational astronomy was chosen because it is a relatively rich knowledge domain composed of a number of concepts with complex causal relations. It is therefore an area where there is the potential for developing rich domain-specific theories. In addition, children's everyday experience provides them with enough information to develop an intuitive understanding of many of the phenomena that are part of the domain of scientific astronomy (e.g., the shape of the earth, the day/night cycle, the phases of the moon, etc.). Finally, theories in astronomy have undergone several major restructurings in the course of the field's development (Berry, 1961; Kuhn, 1957, 1970; Toulmin & Goodfield, 1961). We thought that by selecting a domain of knowledge which has undergone radical restructuring in its historical development as a science we would maxi-

mize our chances of finding similar radical changes in children acquiring knowledge in this domain.

The Concept of the Earth in the History of Astronomy

The concept of the earth is a core construct in any theory of astronomy and has been involved in a number of revolutions in the history of science. The earliest recorded conceptions about the earth were that it was flat and that it stood in the center of the universe. The earth was hypothesized to be flat in early Egypt (Kuhn, 1957; Plumley, 1975), in Sumeria (Lambert, 1975), in early Greece (Toulmin & Goodfield, 1961), and in early India (Gombrich, 1975).

In the historical development of cosmological theories, the view that the earth was flat was eventually replaced by the view that it is a sphere. Aristotle, in his book *On the Heavens,* offered a number of arguments for the position that the earth is a sphere (see Kuhn, 1957). One of the arguments was based on the position of the North Star. The Greeks knew from their travels that the North Star appeared lower in the sky when viewed from a location in the south than from a location farther north, a change which is difficult to explain if one assumes that the earth is flat. Another argument was based on Aristotle's explanation of the eclipses of the moon. Aristotle hypothesized that the eclipses of the moon were caused by the earth's shadow on the moon. Since this shadow was always round, he argued that the earth must be spherical.

The view that the earth is a sphere was fully elaborated by Ptolemy in the *Almagest* (1984). According to Ptolemy, the earth was a sphere which stood motionless at the center of the universe. It was surrounded by eight spheres on which the sun, the moon, the five planets known at the time, and the stars were attached. The sun, moon, and planets moved around the earth in orbits that were perfect circles. The stars were attached to the outermost sphere, which rotated around the earth. The Copernican revolution retained the view that the earth is a sphere, but required a shift from a geocentric to a heliocentric universe and with it the rejection of the belief that the earth does not move.

In the present study we have examined only the changes in children's views about the shape of the earth. We intend to present data about other aspects of children's views of observational astronomy (e.g., the day/night cycle) in future papers.

Children's Ideas about the Shape of the Earth

A number of science educators have investigated children's knowledge about the shape of the earth and gravity and have concluded that children hold various "notions" about the shape of the earth. This evidence comes

from studies conducted by Nussbaum (1979), Nussbaum and Novak (1976), Sneider and Pulos (1983), and Mali and Howe (1979).

Nussbaum and Novak (1976) showed that 2nd-grade children say that the earth is round, but under more detailed questioning give answers consistent either with a flat earth view or with a number of other alternative views regarding its shape. Five such alternative notions about the earth were discovered. Notion 1 was ascribed to the children who said that the earth is round but answered all other questions as if they believed that the earth is really flat. Notion 2 was ascribed to the children who thought that the earth is round like a ball but who lacked the idea of unlimited space; these children thought that there is ground or ocean which bounds the space below the earth and sky which bounds the space above the earth. The children who held notion 3 lacked the idea of gravity; they believed that objects placed on the "bottom" of the spherical earth would fall. The children who held notion 4 knew that objects placed on the "bottom" of the spherical earth do not fall but did not have a full understanding that Earth's gravity operates by pulling things toward the center of the earth. Finally, the children who held notion 5 provided the culturally accepted responses to the earth-shape and gravity questions.

Nussbaum (1979) further tested the validity of these notions in a developmental study involving Israeli children. The results suggested that notions 1 and 2 should be combined. He also uncovered a new notion according to which the earth was like a huge ball consisting of two hemispheres: an upper hemisphere made up of air or sky and a lower hemisphere consisting of the ground where people live.

These results were further validated in a study by Sneider and Pulos (1983) which showed that most children who were below 10 years of age (grades 3 and 4) held notions 1, 2, or 3, that most of the children aged 13 and over held notions 4 and 5, and that the widest spread of notions was found among 11- and 12-year-olds.

Mali and Howe (1979) investigated the development of the earth shape and gravity concepts among Nepali children coming from urban and rural regions. They note that in Nepal the traditional belief of adults who have no schooling is that the earth is a flat object supported on each of four corners by an enormous elephant. However, the children are taught at school that the earth is a sphere. Mali and Howe tested children ages 8, 10, and 12 with tasks similar to those used by Nussbaum and Novak (1976). Their results showed that the Nepali children formed notions of the earth similar to those of the American children but that they tended to occur at later ages.

However provocative the existing research on children's ideas regarding the shape of the earth may be, many questions are left unanswered about the exact nature of these notions. One important limitation of the

existing studies is that they do not make explicit the exact criteria used to identify children's ideas. Neither do these studies provide us with information regarding the systematicity, consistency, and robustness of children's notions about the shape of the earth. In other words, we do not know how children were classified as holding a given notion and whether these notions were used in a consistent and systematic fashion by the children who were assigned to them.

The Present Study

The purpose of the present study was to further investigate the nature of children's intuitive knowledge about the shape of the earth and to understand how this knowledge changes as children are exposed to the culturally accepted information that the earth is a sphere. We wanted to further investigate the hypothesis that children develop alternative notions about the shape of the earth and to find out whether these notions were well defined and used by the children in a consistent manner.

Two specific hypotheses guided our research efforts. The first was that children start the knowledge acquisition process by assuming that the earth is flat. The view that the earth is flat is supported by everyday experience and agrees with prior research regarding children's ideas about the earth.

The second hypothesis was that children will have difficulty understanding the information that the earth is a huge sphere, surrounded by space. The idea that we live all around on the outside of a spherical earth is counter-intuitive and does not agree with everyday experience. In the history of science, the spherical earth view was often attacked by proponents of the flat earth view, for example, on the grounds that people "on the other side" of the earth would fall off (Kuhn, 1957).

The hypothesis that children will find the information regarding the spherical shape of the earth difficult to believe is consistent with reports regarding the construction of alternative notions about the shape of the earth found in the existing research literature. Alternative notions can be seen as attempts on the part of the children to reconcile the information coming from adults that the earth is a sphere with an original naive conception of a flat earth. This view has been an implicit hypothesis in some of the work on students' alternative conceptions in science, but the research to support it has not been done (see Wiser & Carey, 1983, for a discussion of this issue). For example, Piaget (1929, p. 296) reports an interesting case of an "alternative notion" formed by children attempting to understand the phenomenon of the day/night cycle. These children had been given an explanation of the day/night cycle in terms of the rotation of the earth; they had been told that when it was night in Europe it was day in America. They interpreted this information, in the context of their

existing conceptual structures, by constructing the idea that the earth is like a "layer cake." They developed the view that there is a flat earth America under the flat earth Europe and that at night the sun dropped through the European layer and illuminated the lower American layer. Notice that by developing this notion the children succeeded in retaining both their belief that the earth is flat and the information given by adults that when it is night in Europe it is day in America.

Methodology

The basic methodology used in this study consisted of asking children questions (e.g., "What is the shape of the earth?") and eliciting drawings (e.g., "Make a drawing of the earth") in the context of an individual interview. Given that children in our culture are exposed to the information that the earth is a sphere at an early age, we considered it important to ask questions which had the potential to test the generativity of this knowledge and to uncover possible misinterpretations.

In order to examine the range of children's knowledge about the earth we asked children two kinds of questions: those we called *factual* and those we called *generative*. Consider, for example, the question "What is the shape of the earth?" It is possible that children who have been told that the earth is a sphere answer this question by simply repeating the information they have received from adults. Questions of this sort, which we call "factual," provide information regarding children's exposure to certain theoretically important facts, but not about their ability to use these facts in a generative way.

Generative questions have a far greater potential for providing information about children's underlying conceptual structures. These questions ask children to explain phenomena which they cannot directly observe and about which they are not likely to have received any direct instruction. Consider, for example, the questions "If you were to walk for many days in a straight line, where would you end up?" "Would you ever reach the end or edge of the earth?" and "Does the earth have an end or an edge?" In order to answer these questions children cannot rely on some unassimilated piece of information they have received from adults. Rather, they need to create a mental representation of the earth which includes information about its shape and use this mental representation to provide an answer to the question.

Mental Models

Researchers in cognitive psychology and cognitive science have proposed a wide variety of kinds of representations—e.g., propositions (Anderson & Bower, 1973), images (Kosslyn, 1980; Paivio, 1971), semantic nets (Collins & Loftus, 1975), schemas (Brewer & Nakamura, 1984;

Rumelhart, 1980), and mental models (Johnson-Laird, 1981, 1983). We have adopted the construct of the mental model to characterize children's representations in observational astronomy. The construct of the mental model has been used in a number of different ways (e.g., Johnson-Laird, 1983; Gentner & Stevens, 1983; see Brewer, 1987, for a discussion of this issue). It is used here to refer to a particular kind of mental representation which differs from other kinds of representations in that it is an analog to the state of affairs (perceived or conceived) that it represents (see Johnson-Laird, 1983).

We assume that a mental model is a dynamic structure which is created on the spot for the purpose of answering questions, solving problems, or dealing with other situations. Mental models are generated from and constrained by underlying conceptual structures. Thus, if one is told that "The tree is to the right of the house and the wombat is to the right of the tree," one can form a mental model of their relations such that one represents the house to be to the left of the wombat. However, the construction of this particular model is constrained by an underlying conceptual structure related to the properties of Euclidean space.

Similarly, if one is told that "While the astronaut was in the spaceship he dropped the hammer," one's mental model of the location of the hammer after it is dropped will be constrained by an underlying structure related to the assumed properties of gravity. Because we believe that mental models are generated and constrained by people's underlying conceptual structures, we think that understanding the mental models individuals use to answer questions or solve problems provides information about the content and structure of their underlying knowledge base.

METHOD

Subjects

The subjects for this study were 60 children: 20 first graders, ranging in age from 6 years and 4 months to 7 years and 5 months (mean age, 6 years and 9 months); 20 third graders ranging in age from 9 years and 3 months to 10 years and 3 months (mean age, 9 years and 9 months); and 20 fifth graders ranging in age from 10 years and 3 months to 11 years and 9 months (mean age, 11 years). The children attended an elementary school in Urbana, Illinois. They came from middle-class backgrounds. Approximately half of the children were girls and half were boys.

Materials

The materials consisted of a 48-item questionnaire. The questionnaire was developed through extensive pilot work and was designed to provide information about children's knowledge of certain critical concepts in the domain of astronomy. Only the 15 questions about the shape of the earth will be discussed in this paper. These questions are described in detail below.

Questions. Question 1, "What is the shape of the earth?" was a straightforward question

designed to provide information about children's factual knowledge regarding the shape of the earth. Question 2, "Which way do we look to see the earth?" was included in the questionnaire because it was found by Nussbaum and Novak (1976) to be associated with the belief held by some children that there is a spherical earth which is up in the sky.

Questions 3, 4, and 5, "What is above the earth?" "What is below the earth?" and "What is to the sides of the earth?" had the potential of differentiating children who conceptualized the earth as a sphere in space from those who thought of it as flat and supported by ground. Thus, we expected children who thought of the earth as a sphere to say that it is surrounded by space and space objects, while flat earth children were expected to say that there is ground or dirt below and perhaps to the sides of the earth. It turned out that these three questions were not as informative as we had expected. Almost all children said that there is sky or space above and to the sides of the earth, or mentioned the presence of the sun or the moon. The question, "What is below the earth?" was typically interpreted from a flat earth perspective, to refer to the area directly below the ground and thus generated responses like "dirt" or "ground." Because the data from these questions were not useful in differentiating children with spherical earth models from children with flat earth models, they were not used in assigning earth models to children.

Question 6, "Can you draw a picture of the earth?" provided additional information about children's ideas regarding the shape of the earth. If children drew a line or a rectangle earth in response to this question, they were asked the follow-up question, "Is this how the earth would look if we were in a spaceship?" The second question was meant to distinguish children who might have known that the earth is spherical but did not take the spherical earth perspective in their drawing, from children who actually thought that the earth is flat. Obviously, only the former would change their drawings under the second question.

Question 6 was also used as a basis for a number of additional drawings which we hoped would help us better understand children's conceptual knowledge about the earth. For example, in Question 7, "Now on this drawing, show me where the moon and stars go. Now draw the sky," we asked the children to add the stars, the moon, and the sky to their drawing of the earth. The purpose of this question was to help us differentiate the children who thought of the earth as a sphere located in space with solar objects all around it from those who thought that the stars, moon, and sky are found only above the top part of the earth. Asking the children to draw the sky may appear to be strange to an adult, but we felt it was important to distinguish the children who thought the sky was located only above the top part of the earth from those who thought it was something that surrounds the earth. Prior research by Nussbaum and Novak (1976) has shown that some children think that the sky is located only above the top part of the earth and that there is ground or water in the area directly "below" the spherical earth.

In Question 8 the children were asked "Show me where the people live" with respect to their earth drawing. Again here, we wanted to see if the children conceptualized the earth as a sphere with people living all around it, on the outside, or whether they thought that people live only on the top part of the earth.

In Question 9, we attempted to create a conflict between the everyday perception of a flat earth and the culturally accepted information that the earth is a sphere and to obtain children's explanations of this conflict. This question was presented only to the children who indicated that the earth is round in their response to Question 1 and drew a circle or a sphere to depict the earth in their drawings. In this question, the experimenter presented to the child the picture of a house located on what appeared to be a flat landscape and asked, "Here is a picture of a house. This house is on the earth, isn't it?" Assuming that the child would agree that the house is located on the earth, the experimenter went on to ask, "How come here the earth is flat but before you made it round?" By asking this question we wanted to find out whether the children would be able to explain the apparent inconsistency between the everyday perception of a flat earth and the information coming from adults that

the earth is a sphere. When needed, the follow-up question "Can you explain this a little more?" was added.

Questions 10, 11a, and 11b, "If you walked for many days in a straight line, where would you end up?" "Would you ever reach the end or the edge of the earth?" and "Is there an end or an edge to the earth?" further investigated children's conceptualizations of the shape of the earth. It was hypothesized that in response to Question 10 children would create the mental representation of someone walking on the earth and that depending on their particular mental model of the earth, different responses would be given. Responses of the sort, "I would end up in another state" or "I would end up at the ocean" were further explored with follow-up questions which encouraged the children to say what would happen if they continued to walk on a straight line, taking cars, trains, and boats when needed. Question 11 was designed to reveal children's beliefs regarding a possible end or edge of the earth. The definite article "the" was used in Question 11a (the end or the edge of the earth), instead of the indefinite "an end," to make clear to the children that we were not referring to a number of possible "ends of the earth," such as the end of a country or the end of land and the beginning of ocean. Furthermore, our pilot studies had shown that children use phrases such as "the end of the earth" spontaneously. Question 11b, "Is there an end or an edge to the earth?" was used to differentiate the children who thought that there may be an end to the earth which cannot be reached. The way this question was phrased also allowed the children who did not think there is an end/edge to the earth to clearly say so. Question 12, "Can you fall off that end or edge?" and Question 13, "Where would you fall?" were asked only if the children said that there is an end or edge to the earth; they were designed to further distinguish children's ideas about the nature of this end/edge (for example, to determine whether the edge of the earth was something like the surrounding surface of a spherical earth from which one cannot fall or the edge of a disc-like earth from which one can possibly fall).

The last two questions were asked again in relation to the children's earth drawing. Question 14, "Now, I want you to show me where Champaign is. Where is China?" required that the children indicate the location of Champaign (their hometown) and China with respect to their earth drawings. Question 15, "Now tell me what is down here below the earth," was asked with specific reference to the area below the child's drawing depicting the earth. It was meant to further investigate children's ideas regarding the earth, namely, whether the earth was thought to be surrounded by space or supported by something like ground or water.

Procedure

The children were interviewed individually for between 30 and 45 min. The experimenter made detailed notes of the children's responses which were also recorded using a tape recorder. The scoring of the data was done on the basis of both the transcribed data and the experimenter's notes.

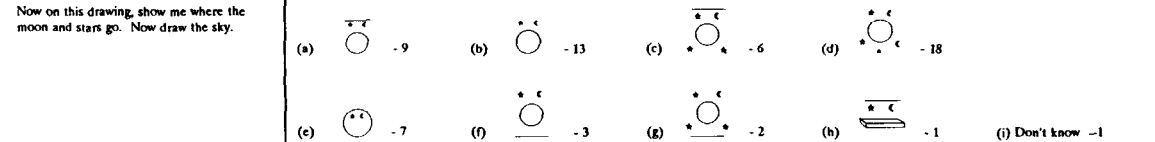
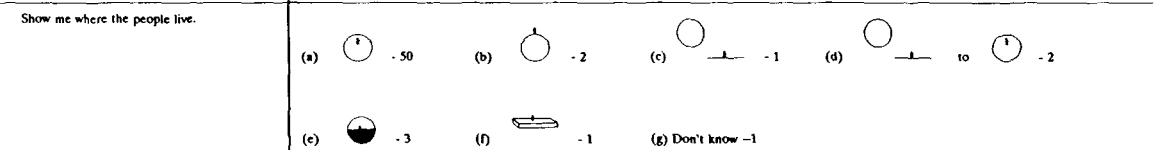
Follow-up questions were used to clarify the responses which we could not understand. The standard procedure we employed was to ask children to "tell us more about it" or to repeat the last part of the child's response as a question, a strategy which usually elicited further information. In a few cases, when we could not at all understand what the children were telling us we were forced to engage in more extensive questioning.

Scoring

The data were scored twice, first at the item level and second at the model level. At the item level, children's individual responses to the questions were scored on the basis of a scoring key containing a set of categories for each question. The scoring categories are shown in Table 1. They were designed to capture the range of specific responses obtained.

TABLE 1

Questions about the Shape of the Earth, Scoring Key Categories, and Frequencies of Children's Responses (N = 60)

Questions		Children's Responses (Scoring Key Categories)
Q1	What is the shape of the earth?	(a) Round - 37, (b) Circle - 16, (c) Round like a ball/sphere - 5, (d) Oval - 1, (e) Don't know - 1
Q2	Which way do we look to see the earth?	(a) Down - 15, (b) Up - 23, (c) Sideways - 7, (d) Everywhere/all around - 12, (e) In the back/forward/straight ahead - 3
Q6	Can you draw a picture of the earth?	(a) Circle - 54, (b) Rectangle/straight line - 1, (c) Circle within square frame - 1, (d) Oval - 2, (e) Flat line but changes to circle after questioning - 2
Q7	Now on this drawing, show me where the moon and stars go. Now draw the sky.	 (a) - 9 (b) - 13 (c) - 6 (d) - 18 (e) - 7 (f) - 3 (g) - 2 (h) - 1 (i) Don't know –1
Q8	Show me where the people live.	 (a) - 50 (b) - 2 (c) - 1 (d) to - 2 (e) - 3 (f) - 1 (g) Don't know –1
Q9	(a) Here is a picture of a house. This house is on the earth, isn't it? (b) How come here the earth is flat but before you made it round? (c) Can you explain this a little more?	(a) Not applicable - 1, (b) Don't know - 1, (c) Changed from round earth to flat earth response - 3, (d) Child does not recognize flat/sphere conflict - 2, (e) The earth is round like a pancake - 6, (f) The earth is flat inside - 14, (g) The earth is round but we live on flat pieces of land - 4, (h) Dual earth - 5, (i) Child recognizes conflict but cannot explain it - 17, (j) The earth looks flat because it is very big - 7
Q10	If you walked for many days in a straight line, where would you end up?	(a) Yes, there is an end/edge - 16, (b) Yes, there is an end/edge but we can't reach it because we are inside the earth - 6, (c) No end/edge and no explanation - 15, (d) No end/edge, you come back to where you started - 15, (e) No end/edge, because the earth is round - 7, (f) No end/edge but the earth is up in the sky - 1
Q11	(a) Would you ever reach the end/edge of the earth? (b) Is there an end or an edge to the earth?	
Q12	Can you fall off that end/edge?	(a) Don't know - 5, (b) Not applicable because there is no end/edge - 32, (c) Yes, you can fall off - 12, (d) Yes, you will fall on the ground - the ground being underneath the earth - 2, (e) No, and no explanation - 3, (f) No, you are inside the sphere - 4, (g) No, gravity will hold you - 2
Q13	Where would you fall?	
Q14	(a) Now, I want you to show me where Champaign is. (b) Where is China?	(a) Both inside circle - 47, (b) One is on other non-visible side of earth - 9, (c) One or both are outside circle - 1, (d) Champaign inside circle but child does not know where China is - 1, (e) Does not know where to place either Champaign or China - 2
Q15	Now tell me what is down here below the earth. (Experimenter points to the area below the circle in the child's drawing)	(a) Sky/atmosphere/clouds - 13, (b) Sun/moon/stars - 18, (c) Space - 14, (d) Dirt/ground/land - 9, (e) Water - 2, (f) Don't know - 4

Agreement between two independent judges who used the scoring key to score all the responses was high (94%). All disagreements were resolved after discussion.

Following the scoring at the item level, we tried to see if we could find evidence in the data for the consistent use of a small number of well-defined mental models of the earth. The scoring at the model level was done on the basis of a second scoring key which outlined the pattern of expected responses for each model. The second scoring key, the procedure for scoring the data at the model level and the reliability of this second scoring procedure will be described later.

RESULTS

Children's responses to the individual questions and their frequencies are shown in Table 1. A first look at the data appeared to show that many children did not make consistent use of the culturally expected spherical earth model. This apparent inconsistency in the obtained responses can be seen even in a superficial examination of the overall frequencies of responses to some key questions. As shown in Table 1, while practically all the children drew a circle to depict the shape of the earth (54 out of 60), 16 said that there is an end or edge to the earth, and 14 said that one can fall off from this end. In addition, 23 children said that you look "up" to see the earth. An example of a response to the questions regarding the end/edge of the earth is given below.

Kristi (1st grade) (Questions 10, 11, 12, and 13, Response type c, fall off)

E: If you walked and walked for many days in a straight line, where would you end up?
C: You would end up in a different town.
E: Well, what if you kept on walking and walking?
C: In a bunch of different towns, states, and then, if you were here and you kept on walking here (child shows the edge of the circle which she had drawn to depict the earth) you walk right out of the earth.
E: You'd walk right out of the earth, huh?
C: Yes, because you just go that way and you reach the edge and you gotta be kinda careful.
E: Could you fall off the edge of the earth?
C: Yes, if you were playing on the edge of it.
E: Where would you fall?
C: You'd fall on this edge if you were playing here. And you fall down on other planets.

Notice in this example that Kristi volunteers the information that the perimeter of the circle which she drew to depict the earth was the "edge" from where "you walk right out of the earth." This response suggests that Kristi may have conceptualized the circle not as a sphere but as a flat disc.

A number of other responses were rather strange from the point of view of a spherical earth model and suggested the presence of alternative conceptions about the earth. For example, in response to Question 7, some children placed the sky in the area directly below the circle which was

drawn to depict the earth (Response types f and g), or placed the moon and stars inside the circle (Response type e). Initially, this response seemed puzzling but when we asked them, the children explained that they meant to put the moon and the stars above the top of the circle and not inside it. It is as if these children viewed the circle as the surface of a disc-shaped or hemisphere-shaped (truncated) earth.

Other children located the people on flat ground outside the circle in response to Question 8 (Response types c and d) or on a flat line inside the circle (Response type e). In response to Question 9, some children said that the earth is round like a pancake (Response type e) or suggested that they believed that there are two earths, one round and one flat (Response type h). Some examples from these types of responses are given below.

Terina (5th grade) (Question 9, Response type e, pancake)

C: The earth is round but when you look at it it is flat.
E: Why is that?
C: Because if you were looking around it would be round.
E: But what is the real shape of the earth?
C: Round, like a thick pancake.

Brandy (1st grade) (Question 9, Response type h, dual earth)

E: How come the earth here is flat but before you said it is round?
C: Because the earth is up in the sky and that's (points to the picture of the house) down on the earth.

Other children argued that the earth is round on the outside, but flat on the inside, where people live (Question 9, Response type f). The inside-the-sphere response was often particularly clear in responses to Questions 10/11 (Response type b) and 12/13 (Response type f). The following is an example of this response type.

Mathew (1st grade) (Questions 10/11 and 12/13, Response types b and f, inside-the-sphere)

E: If you walked and walked for many days where would you end up?
C: If we walked for a very long time we might end up at the end of the earth.
E: Would you ever reach the edge of the earth?
C: I don't think so.
E: Say we just kept walking and walking and we had plenty of food with us.
C: Probably.
E: Could you fall off the edge of the earth?
C: No. Because if we were outside of the earth we could probably fall off, but if we were inside the earth we couldn't fall off.

Were the children in our sample truly inconsistent or could the apparent inconsistency in our data be explained by assuming that they made consistent use of a small number of alternative models about the earth? We decided to start by examining the possibility that the children were using alternative models of the earth in a consistent way, before concluding that they were fragmented and internally inconsistent.

A careful examination of our data, together with the findings of the

prior research in this area, led us to the initial formulation of the four alternative mental models of the earth which appear in Fig. 1 as the disc, rectangular, hollow sphere b, and dual earth models.

Preliminary Earth Models

Disc earth. The first preliminary model was the model of an earth shaped like a disc or like a pancake. The information that the earth is round like a disc rather than round like a ball appeared often in children's responses to Question 9 and was consistent with a number of additional responses, such as the response "circle" to Question 1 and the idea that the earth has an end or an edge from which one can fall off.

Rectangular earth. The second model was similar to the disc model except that the shape of the earth is rectangular instead of circular.

Hollow sphere. The third model of the earth was that of a hollow sphere with people living on flat ground deep inside it. This model resembles in

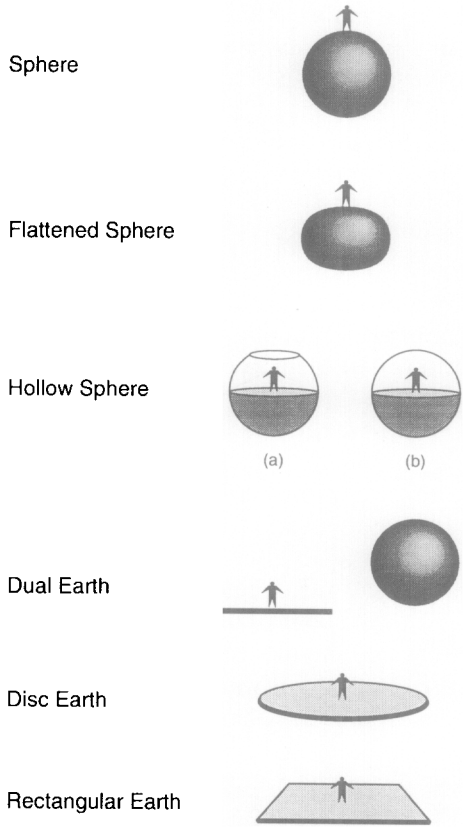


FIG. 1. Mental models of the earth.

some respects the two-hemisphere model identified by Nussbaum (1979) according to which the earth consists of two hemispheres: the lower one, on which people live, and the upper hemisphere which represents the sky, covering the earth like a dome. A number of responses to Questions 9, 10, 11, 12, and 13 indicated the presence of such a model, as was shown in the example from Mathew above. The hollow sphere model is consistent with the drawing (e) to Question 8, which showed the people standing on a flat line inside the circle depicting the earth, as well as with the drawing (e) to Question 7 which showed the moon and the stars inside the top of the circle.

Dual earth. The fourth model was the dual earth model, according to which there are two earths: a round one which is up in the sky and a flat one where people live. This model was consistent with the responses "round" or "round like a ball/sphere" to Question 1 (Response types a and c), the drawing of a circle to Question 6 (Response type a), and the response that there is an end or an edge to the earth from which one can fall off. The dual earth model is consistent with the placement of the people on flat ground outside the circle which is supposed to depict the earth (Question 8, Response type c), with the drawing of the sky below the earth (Question 7, Response types f and g), with the response that there is dirt or ground below the earth (Question 15, Response type d), and with the "dual earth" response to Question 9 (Response type h).

Modification of Preliminary Models

Preliminary patterns of responses. In order to find out whether children's seemingly inconsistent responses were internally consistent with respect to these alternative mental models of the earth, we used the following methodology (see also Siegler, 1978). For each identified earth shape model we generated the pattern of responses expected if the child had used this model consistently to answer our questions. For example, we assumed that if the children had used the mental model of a disc-shaped earth in a consistent way they would say that the shape of the earth is round or circle to Question 1, that one should look down to see the earth, and that there is an edge or an end to the earth from which people can potentially fall off. These children should draw a circle to depict the earth and they should put the people inside the circle. They should place the stars and the moon above the top of the circle and they should say that there is ground or water below it. The preliminary pattern of responses for the hypothesized mental models of the earth appears in Table 2.

Additional models. Once the pattern of responses for each earth-shape model was generated it was applied to the data to determine the degree of correspondence between the expected and obtained responses to the rel-

TABLE 2
Preliminary Pattern of Responses for Hypothesized Mental Models of the Earth

	Question	Sphere	Hollow sphere	Disc earth	Rectangular earth	Dual earth
Q1	What is the shape of the earth?	Sphere/round like a ball, round, oval	Sphere/round like a ball, round, or oval	Circle or round	Rectangle, flat	Flat or round
Q2	Which way do we look to see the earth?	Down	Down	Down	Down	Up or down
Q6	Can you drawn a picture of the earth?	Circle	Circle	Circle	Rectangle, flat line	Flat line or circle
Q7	Now on this drawing show me where the moon and stars go. Now draw the sky.	Response type d[a]	Response type a, b, or e	Response type a or b	Response type h	Response type a, b, c, d, f, or g
Q8	Show me where the people live.	Response type b	Response type e	Response type a	Response type f	Response type a, c, or d
Q9	(a) Here is a picture of a house. This house is on the earth, isn't it? (b) How come here the earth is flat but before you made it round?	The earth looks flat because it is very big	The earth is flat inside	The earth is round like a pancake	Not applicable	The round earth is up in the sky
Q10	If you walked for many days in a straight line, where would you end up?	No end/edge	No end/edge, or Yes, but we can't reach it because we are inside the sphere	Yes, there is an end/edge	Yes, there is an end/edge	Yes, there is an edge
Q11	(a) Would you ever reach the end/edge of the earth? (b) Is there an end/edge to the earth?					
Q12	Can you fall off the end/edge?	Not applicable, or No, gravity will hold you	Not applicable, or No, you are inside the sphere	Yes, you can fall off	Yes, you can fall off	Yes, you can fall off
Q13	Where would you fall?					
Q14	(a) Now I want you to show me where Champaign is. (b) Where is China?	Both inside circle, or one is on other nonvisible side of earth	Both inside circle	Both inside circle	Both inside rectangle	Inside circle, or on flat ground outside it
Q15	Now tell me what is down here below the earth.	Sky, space, sun/moon/stars	Sky, space, sun/moon/stars	Dirt/ground, water	Dirt/ground, water	Sky, sun/moon/stars, or ground

[a] Response types are indicated in Table 1.

TABLE 3
Expected Pattern of Responses for Final Mental Models of the Earth

	Question	Sphere	Flattened sphere	Hollow sphere	Disc earth	Rectangular earth	Dual earth
Q1	What is the shape of the earth?	Sphere/round like a ball, round or oval (circle)[a]	Round, oval, or circle	Sphere/round like a ball, round, oval or circle	Circle or round	Rectangle, flat	Sphere/round like a ball, round or circle
Q2	Which way do we look to see the earth?	Down, sideways or all around (up)	Down, sideways, or all around (up)	Down, sideways, all around or up	Down, sideways, or all around (up)	Down, sideways or all around (up)	Up
Q6	Can you draw a picture of the earth?	Circle	Circle	Circle	Circle	Rectangle, flat line	Circle
Q7	Now on this drawing show me where the moon and stars go. Now draw the sky.	Response type a, b, c, or d[b]	Response types a, b, c, or d	Response types a, b, c, d, or e	Response types a, b, or e	Response type h	Response types a, b, c, d, f, or g
Q8	Show me where the people live.	Response types a or b	Response types a or b	Response types a or e	Response type a	Response type f	Response types a, b, c, or d
Q9	(a) Here is a picture of a house. This house is on the earth, isn't it? (b) How come here the earth is flat but before you made it round?	The earth looks flat because it is very big, or Child recognizes conflict but cannot explain it (It is round but people live on flat pieces of land)	The earth is round like a pancake	The earth is flat inside	The earth is round like a pancake	Not applicable	The round earth is up in the sky

Q10 If you walked for many days in a straight line, where would you end up? Q11 (a) Would you ever reach the end/edge of the earth? (b) Is there an end/edge to the earth?	No end/edge (Yes end/edge, but you cannot fall off because of gravity)	No end/edge	No end/edge, or Yes, there is an end/edge but we can't reach it because we are inside the earth	Yes, there is an end/edge	Yes, there is an end/edge	Yes, there is an end/edge, or No end/edge because round earth is up in the sky
Q12 Can you fall off the end/edge? Q13 Where would you fall?	Not applicable, or can't fall off because of gravity	Not applicable	Not applicable, or No, you are inside the sphere	Yes, you can fall off	Yes, you can fall off	Yes, you can fall off
Q14 (a) Now I want you to show me where Champaign is. (b) Where is China?	Both inside circle, or one on other non-visible side of earth	Both inside circle, or one on other non-visible side of earth	Both inside circle, or on a flat line inside the circle	Both inside circle	Inside rectangle	Inside circle or on a flat line outside circle
Q15 Now tell me what is down here below the earth.	Sky, space, or sun/moon/stars	Sky, space, or sun/moon/stars	Sky, space, or sun/moon/stars (dirt, ground)	Dirt/ground, water	Dirt/ground, water	Sky, sun/moon/ stars or ground

[a] Responses in parenthesis indicate acceptable deviations.
[b] Response types are indicated in Table 1.

evant earth-shape questions. During this first scoring at the model level, it became apparent that a number of modifications of the pattern of responses were needed. First of all, the data suggested the need for a new model—the "flattened sphere" model. This new model was very similar to a spherical one, surrounded by space, but flattened at the "top" and "bottom" where the people live (see Fig. 1).

Analysis of the data also suggested a reexamination of the patterns of expected responses for both the dual earth model and the hollow sphere model. Most of the children who had constructed the model of a dual earth seemed to apply the term "earth" to only the round earth and used the term "ground" to refer to the flat earth on which people live.

In the case of the hollow sphere model, there seemed to be two variations: Some children thought that the earth consists of two hemispheres, the lower one being the hemisphere on which people live and the upper one being the sky which covers the earth like a dome (Fig. 1, hollow sphere b). Others thought that people live deep inside a pumpkin-like earth open at the top (Fig. 1, hollow sphere a).

Scoring criteria. In setting up our new scoring criteria, we tried to take into consideration children's limitations in drawing, particularly in representing three-dimensional space. Furthermore, we decided that it was necessary to distinguish responses which were totally inconsistent with a given mental model of the earth and those responses which were indeterminant with respect to a given mental model. In order to make this distinction, we created the categories of *unacceptable deviations* and *acceptable deviations*. An *unacceptable deviation* is a response inconsistent with the mental model in question. For example, the response that the earth has an end or an edge from which someone can fall is inconsistent with the mental model of a spherical earth. Even one unacceptable deviation was enough to prevent a child from being assigned to a given model. An *acceptable deviation* is a response which, while in principle inconsistent with the mental model in question, can nevertheless be explained on the grounds that it represents a semantic error or is ambiguous with respect to its exact meaning. An example of an acceptable deviation is the response "circle" to Question 1. For children who otherwise hold a spherical earth view, it is not clear whether this response is related to a conceptual confusion (i.e., the child is using the word "circle" to refer to a disc-shaped earth), or a semantic error (i.e., the child is using the word "circle" to mean "round like a ball"). Because we wanted to be strict in our criteria for assigning models and not be accused of manufacturing consistency, we decided to allow only one acceptable deviation per child.

The modified scoring criteria were used by the two authors to assign children to mental models. A third independent judge was given one third of the protocols and the written criteria for the models as presented in

Table 3. The scorer coded the mental models without any discussion about the criteria with the original coders. The agreement was 80% (16 out of 20 cases). After all the disagreements were discussed 10 new protocols were scored by the independent judge. The resulting agreement was 100%.

Final Earth Models

Pictures of the five final mental models are given in Fig. 1, and the final criteria used to assign children to these models are given in Table 3. The items in parentheses show the acceptable deviations for each model. In the section that follows we will discuss in detail the pattern of expected responses as well as the acceptable and unacceptable deviations for each mental model of the earth.

Spherical earth model. We expected a child with a spherical earth model to say that the earth is "a sphere," "round like a ball," "round," or "oval" to Question 1. The response "circle" was ambiguous with respect to the mental model of the earth it denoted (for the reasons already explained) and was therefore placed in the acceptable deviation category.

With respect to Question 2, "Which way do we look to see the earth?" the expected responses for the spherical earth model were "down," "sideways," and "all around." However, an unexpectedly large number of children (23/60), including the majority of the 1st graders (12/20) said that you look "up" to see the earth. This result made us question the prediction that this response would be given only by children who believed the earth to be up in the sky. In retrospect, it appears that the response "up" for this item can also be given by children who interpret "looking up at the horizon" or "looking up at the mountains" to mean that the earth is "up." It could also be given by children who are used to hearing a teacher telling them, "Let's look up at the earth" in reference to a map of the earth on the wall.[1] Because of the ambiguity associated with the response "up," this response was considered an acceptable deviation for the spherical earth model.

In Question 6, all circular or oval-shaped earth drawings were considered consistent with the adoption of a spherical earth mental model. The drawing of a rectangle was considered an unacceptable deviation.

From the point of view of a child who used a spherical earth model in a consistent manner, one would expect to see drawings where the moon, the stars, and the sky were placed all around the circle (Response type d). However, drawings depicting the sky with a horizontal line located above

[1] We are indebted to Rochel Gelman for drawing our attention to research being conducted at Pennsylvania State University which shows that children code maps of the world with reference to the terms they hear their teachers use.

the top of the circle and the placement of the stars and moon above the top of the circle could represent conventional ways of drawing the sky and the moon or could be given by someone who believed that people live only at the top of the spherical earth. For this reason, these three response types (a, b, and c) were considered consistent with a spherical earth model. The placement of the stars and moon inside the circle (Response type e) and the drawing of a horizontal line beneath it (Response types f and g) were considered evidence for alternative models and therefore inconsistent with the adoption of a spherical earth model.

Responses to Question 8, "Show me where the people live" showed that most children (50/60) drew their people inside the circle (Response type a). Only two children placed their people on the perimeter of their round earth drawings. It appears that most children found it too difficult to make a realistic drawing of a sphere with people standing on the perimeter and therefore drew their people inside the circle. We considered this response consistent with the spherical earth model. Drawings of people standing on a flat line inside the circle (Response type e) or a flat line outside the circle (Response type c) were associated with alternative earth models and were considered unacceptable deviations for this category.

Similarly, in response to Question 14 we considered all responses showing Champaign and China to be inside the circle to be consistent with the spherical earth model. Only the response indicating that China is outside the circle (Response type c) was considered unacceptable from the point of view of a spherical earth model.

In Question 9 we considered a response consistent with the spherical earth model if it provided some indication that the child understood the flat/sphere conflict, even though he or she could not provide a complete explanation (Response types i and j). The response, "it is round but people live on flat pieces of land" was considered to be an acceptable deviation (Response type g). The responses, "It looks round but it is flat inside," "It is flat like a pancake," etc., were interpreted as indications of alternative earth models and were considered unacceptable deviations from the spherical earth model.

Responses to all the questions regarding the end/edge of the earth (Questions 10, 11, 12, and 13) were considered together when assigning children to the spherical earth model. The expected response for placement in this category was that the earth does not have an end or an edge. A negative response to these questions made the questions regarding falling off the earth inapplicable (Questions 12 and 13, Response type b). A positive response to the end/edge questions was considered unacceptable from the point of view of a spherical earth child. There is, however, a small ambiguity associated with this response, in that it leaves open the possibility that a spherical earth child may have interpreted "edge" to mean the outer surface of the earth. In such a case this child could not

claim, however, that people can fall off of this end or edge. There were two children in our sample who said that there is an end/edge to the earth but one cannot fall from there because of gravity. This response was considered an acceptable deviation for placement in the spherical earth category. Responses which indicated that the earth has an end or edge from which one can fall off were considered unacceptable deviations.

Finally, the expected responses for Question 15 regarding the area below the child's drawing of a circle were considered to be sky, space, or solar objects. Responses such as ground, dirt, or water were considered indications of a dual earth or a disc model and were considered unacceptable deviations for the spherical earth model.

Spherical earth data. Twenty-three children met the requirements for placement in the spherical earth category. The acceptable deviations observed were the following. One child said "circle" in response to Question 1, three children said "up" in response to Question 2, and one child said there was an "end" to the earth from which we could not fall off because of gravity. As has already been mentioned, only one acceptable deviation per child was allowed.

The following is a typical example of a child who used the mental model of a spherical earth consistently.

Ethan (1st grade) (Subject number 5, sphere model)

E: What is the shape of the earth?
C: It's the shape of a ball.
E: Which way do we look to see the earth?
C: Down.
E: What is above the earth?
C: Space.
E: What is below the earth?
C: Space.
E: Can you draw a picture of the earth?
(The child draws the picture shown in Fig. 2a)
E: Show me where the moon and stars go.
C: Well, the stars go all around it, and the moon could probably be up here. And here could be the sun.
E: Now draw the sky.
C: The sky has no shape. You mean space. I can draw the sky around the earth.
E: How come here the earth is flat but before you made it round?
(The child is shown the picture of a farm house on what appears to be a flat earth.)
C: Well the earth is so big it looks flat but it's round. If it's round and it's huge, people see it as flat. I think the islands are on flat, I think. I think the islands are a bit curved but people don't notice it.
E: If you walked and walked for many days in a straight line, where would you end up?
C: Back where you started.
E: Would you ever reach the end or the edge of the earth?
C: No, because gravity pulls you down.
E: Is there an end or an edge to the earth?
C: No.

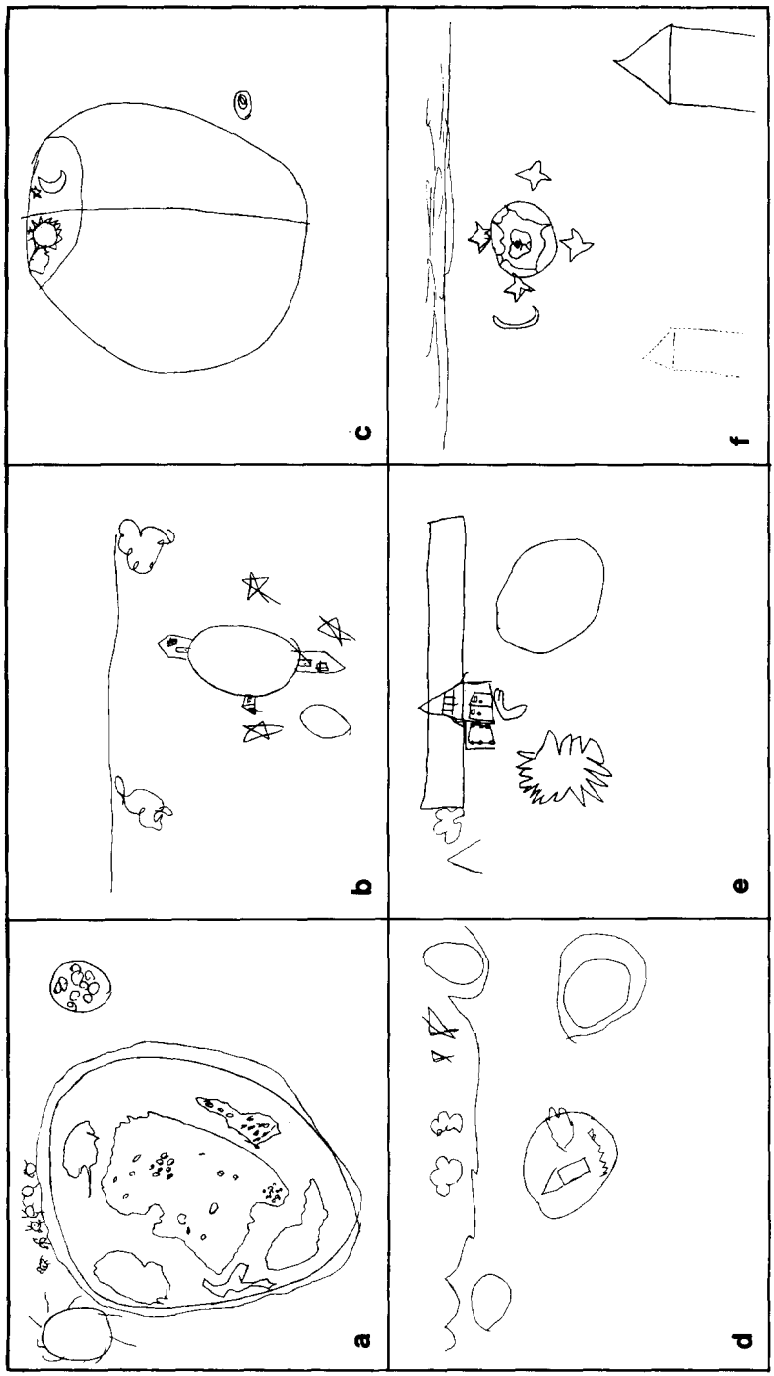


FIG. 2. Drawings of the earth, the moon, the stars, and the sky for the children whose protocols are used as examples. (a) Ethan, Grade 1 (spherical earth); (b) Brian, Grade 1 (flattened sphere); (c) Venica, Grade 3 (hollow sphere); (d) Jamie, Grade 3 (disc earth); (e) Donald, Grade 1 (rectangular earth); (f) Darcy, Grade 3 (dual earth).

Flattened sphere model. Children were placed in this category if they gave a pattern of responses consistent with the view that the earth is a flattened sphere or a thick pancake surrounded by space. These children did not seem to have a problem with the idea that people can live around the earth, on the outside, but they appeared to have particular difficulty with the idea that the earth can be both round and flat at the same time. They apparently solved this flat/sphere conflict by thinking of the earth as partly flattened on the "top" and on the "bottom" where people live.

The children placed in this category were expected to say that the earth is "round," "oval," or "circle" in response to Question 1. The response "sphere or round like a ball" was not consistent with this model and therefore was considered an unacceptable deviation for this category.

Children with a flattened sphere model were expected to give responses to Question 2 similar to those expected from children with a spherical model. They could point downward, sideways, or all around when asked "Which way do we look to see the earth?" The response "up" was considered an acceptable deviation for the reasons already discussed. In response to Question 6, they were expected to draw a circle, and in Question 7, to place the moon and stars either above the top of the circle or all around it (Response types b or d). The drawing of a horizontal line to indicate the sky was considered acceptable for the reasons already discussed in the sphere model, but only if the sky was located above the top of the earth (Response types a and c), not below it (Response types f and g).

In response to Question 8 the children who used the flattened sphere mental model were expected to place the people either inside the circle or on the perimeter of the circle. On Question 14 children with the flattened sphere model were expected to place Champaign and China inside the circle or on the nonvisible side of the earth. The children in this category did not have a problem with the idea that people live on the outer surface of the earth. Their problem was in finding an explanation of the flat/sphere conflict. They seemed perplexed by the fact that the earth appears to be flat when it is said to be spherical. In an attempt to explain this apparent contradiction they created a flattened sphere mental model in which the earth is like a thick pancake, flat on the top and the bottom but curved on the sides. This mental model was made explicit in their responses to Question 9, "How come here the earth is flat but before you made it round?", where they all said that the earth is round like a pancake (Response type e). This response was very diagnostic for this model, which in most other respects resembles the spherical earth mental model.

In response to Questions 10 and 11, the children with a flattened sphere model said that there is no end/edge to the earth and that one can walk back to where one started (Response types c, d, or e). Again, this was the

case because these children appeared to know something about gravity and to understand that people do not fall off the earth. Questions 12 and 13 regarding falling off the earth were not applicable since these children were expected to say that there is no end/edge to the earth.

Finally, children with a flattened sphere model were expected to say that there is space, sky, or sun/moon/stars below the earth in Question 15, because they knew that the earth is surrounded by space. The responses "ground" or "water" were unacceptable.

Flattened sphere data. Four children were placed in this category and all of these children explained the flat/sphere conflict by saying that the earth is flat and round like a thick pancake. One child said that people live on flat pieces of land but later when asked explicitly whether the earth was round like a ball or round like a pancake he responded by saying that it is round like a pancake. All the children in this category also said that there is no end/edge to the earth and stated that there is space, sky, or solar objects below the earth. One child gave an "up" response to Question 2 and two other children drew a horizontal line to depict the sky in Question 7. These were the only acceptable deviations observed. As before only one acceptable deviation was allowed for a given child.

Here is an example from the protocol of a child who was classified as holding the flattened sphere model.

Brian (1st grade) (Subject number 43, flattened sphere model)

E: What is the shape of the earth?
C: Round.
E: Which way do we look to see the earth?
C: Around.
E: Make a picture of the earth so that its real shape shows.
(Child draws the picture of the earth, the moon, the stars, the sky which is indicated in Fig. 2b).
E: Here is a picture of a house. This house is on the earth isn't it? How come here the earth is flat but before you made it round?
C: Because the earth has . . . it's round and it's flat on each side.
E: If you walked and walked for many days in a straight line where would you end up?
C: Mexico.
E: What if you kept walking?
C: Florida.
E: And kept on walking?
C: California.
E: Would you ever reach the end or edge of the earth?
C: No.
E: Why not?
C: Cause the ground's the earth and it's only . . .
E: Tell me in this picture what is down here below the earth?
C: The moon.
(The child is questioned again at the end of the interview.)

E: Let me ask you a couple more questions. See this picture of the earth is flat here, but before you made it round, how come?
C: Because it's flat on each side.
E: (The experimenter gives the child some clay.) Can you make the earth whatever shape it is?
C: (Child makes a pancake flat on each side.)
E: O.K., now where is it flat?
C: Right here and here (shows the "top" and the "bottom" of the pancake).
E: Before you said it was flat like a pancake, is that true or is it a different kind of flat?
C: Yes, it's flat like a pancake.

Hollow sphere model. Children were placed in this category if they gave a pattern of responses consistent with the view that (a) the earth is a hollow sphere and that people live deep inside it, or (b) that the earth consists of two hemispheres: a lower hemisphere on which people live and an upper hemisphere which consists of the sky and which covers the earth like a dome (see also Nussbaum, 1979).

All responses to Question 1 were acceptable for placement in this model. We considered "circle" to be an acceptable response in the case of the hollow sphere models, because it is consistent with the view that the earth consists of two hemispheres and that the top of the lower hemisphere on which people live forms a circle.

All classes of responses were also permitted in Question 2, "Which way do we look to see the earth?" because from the point of view of a hollow sphere model the earth can be "down," "to the sides," or even "up." The response "everywhere" or "all around" was, however, considered to be particularly diagnostic of this model, because from the point of view of a hollow sphere the earth is indeed all around us. The children were expected to draw a circle to indicate the shape of the earth in Question 6. Flat earth responses to these questions were considered unacceptable deviations.

In response to Question 7, a child with a hollow sphere model could place the moon and stars all around the circle, above the top of the circle or inside the top half of the circle (Response types a, b, c, d, and e). Response type e (moon and stars inside top half of the circle) was unacceptable for the spherical earth and flattened sphere mental models, but makes good sense for a child with a hollow sphere mental model who thinks that people live on the earth's lower hemisphere and that the sky is an upper hemisphere covering the earth like a dome. Children in this category were expected to have an understanding of space and to think that the earth is a sphere suspended in space. Yet, we also expected them to have some difficulty with the notion of the sky, particularly those who believed that the sky is a dome covering the top of the hemisphere-like earth. For this reason the use of a horizontal line to depict the sky and the

placement of this horizontal line above the top of the circle (Response types a and c) was considered consistent with this model. The placement of the horizontal line below the circle does not make sense from the point of view of the hollow sphere model and was considered an unacceptable deviation (Response types f and g).

In response to Question 8 we expected children with hollow earth models to place the people either inside the circle or on a flat line inside the circle (Response types a or e). Response type e (on a flat line inside the circle) was scored as an expected response only for the hollow sphere mental model because this is the only model for which this drawing seems to make sense. Placing the people on the perimeter of the circle on the outside was considered an unacceptable deviation for this model (Response type b). Similarly, responses such as drawing the people on a flat line outside the circle were unacceptable deviations which excluded children from placement in this category (Response types c or d). It is interesting to note that some of the children in this category who placed their people inside the circle drew them at the very bottom of the circle, sometimes with their feet touching the bottom inner part of the circle, as they would stand if they were deep inside the sphere.

In Question 14 we expected children with a hollow sphere model to place Champaign and China either inside the circle or on a flat line inside the circle. All other responses to these questions were considered unacceptable deviations.

We considered it crucial that the children placed in this category explain the flat/sphere conflict in Question 9 from the point of view of a hollow sphere model, because this question gives them a real opportunity to provide qualitative evidence for their mental model. We therefore expected children who used a hollow sphere mental model to say that the earth is spherical when seen from the outside, but that it looks flat to us because we live on flat ground *inside* the earth (Response type f). All other responses to this question were considered unacceptable deviations.

Children's responses to Questions 10/11 and 12/13 regarding the end/edge of the earth were also important for placement in this category. Here a number of responses were possible. If children thought that the sky covers the earth like a dome, we expected them to say either that the earth does not have an end/edge (Response type c) or that it has an end/edge but that we cannot fall off of it, because the dome of the sky covers the end/edge of the earth (see the example for Amanda, Subject number 48, below—Response type a to Questions 10/11, followed by Response type f to Questions 12/13). If children thought that the earth is a hollow sphere, open at the top, with people living deep inside it, they could say that there is an end/edge to the earth, but that this end/edge is

very high up and people cannot reach it (Response type b). See the protocol for Venica, Subject number 33, given below, for an example of this type of response.

Finally, the expected responses to Question 15, "What is down here below the earth?" were "space," "sky," or "sun/moon/earth" because for a hollow earth model the earth is a sphere surrounded by space. The responses "ground," "dirt," or "water" were considered acceptable deviations because some of the children with a hollow sphere mental model seemed to interpret this question to refer to the material that was inside the earth but below the flat ground on which the people live.

Hollow sphere data. Twelve children with well-defined hollow sphere models were placed in this category. They all said explicitly that the earth is a sphere but that people live on flat ground inside it in response to Question 9 about the flat/sphere conflict. In response to Questions 10/11 about the end/edge of the earth, the children in this category either denied that there is an end/edge to the earth or said that if there is one it is too high up and cannot be reached because we are inside the sphere. One child (Amanda, Subject number 48) who apparently had formed a two-hemisphere hollow earth mental model said that there is probably an end/edge to the earth but that we cannot fall off that end because we are inside the earth. Upon further questioning, the child revealed that she believed that the sky was at the end of the earth. Here is an excerpt from this child's interview:

Amanda (1st grade) (Subject number 48, hollow sphere model)

E: What if we were standing at the end of the earth, would we fall?

C: No. But we could probably bump into something.

E: What does the end of the earth look like? What do you imagine it to be?

C: Just an end of the . . . um . . . sky.

Five out of the 12 children in this category drew the stars, moon and/or sky inside the circle, three drew the people on a flat line inside the circle, and six said that the earth is "all around" us when asked "Which way do we look to see the earth?", a response which was very rare in the children assigned to the other earth shape categories.

The only acceptable deviations observed for children classified in this category were the response "rocks" or "soil" to Question 15, "What is here below the earth?" given by two children and the response "ocean" by another child who apparently believed that there is an ocean below the earth.

Here is a typical example from the protocol of a child who was classified as holding the hollow sphere model.

Venica (3rd grade) (Subject number 33, hollow sphere model)

(Venica drew the picture of the Earth shown in Fig. 2c.)

E: How come here the earth is flat but before you made it round?

C: Because you are on the ground and you make that picture like a shape and you made it a square shape and if you'll look up it'll look like a rectangle or something like that and if you go out of earth and go into space you'll see a circle or round.
E: So what is the real shape of the earth?
C: Round.
E: Why does it look flat?
C: Because you are inside the earth.
E: If you walked and walked for many days in a straight line, where would you end up?
C: Somewhere in the desert.
E: What if you kept walking?
C: You can go to states and cities.
E: What if you kept on walking?
C: (No response.)
E: Would you ever reach the edge of the earth?
C: No. You would have to be in a spaceship if you're going to go to the end of the earth.
E: Is there an edge to the earth?
C: No. Only if you go up.

Later:

E: Can people fall off the end/edge of the earth?
C: No.
E: Why wouldn't they fall off?
C: Because they are inside the earth.
E: What do you mean inside?
C: They don't fall, they have sidewalks, things down like on the bottom.
E: Is the earth round like a ball or round like a thick pancake?
C: Round like a ball.
E: When you say that they live inside the earth, do you mean they live inside the ball?
C: Inside the ball. In the middle of it.

Disc earth model. This mental model represents the earth as a disc supported by ground. Unlike the children with a flattened sphere mental model, the children with a disc model were very similar to those who held the model of a flat, rectangular earth. These children thought of the earth as a disc, with dirt or water below it and sky directly above it.

The expected pattern of responses for the disc mental model is shown in Table 3. "Round," or "circle" were the expected responses to Question 1, and "down," "all around," or "sideways" were the expected responses to Question 2. "Up" was considered an acceptable deviation for the reasons already mentioned. These children were expected to draw a circle to depict the earth in response to Question 6 and to place the moon and stars either above the top of the circle or inside it (Question 7, Response types a, b, or e). Placing the moon and stars all around the disc was an unacceptable deviation for this model, because the disc is supposed to be rooted in the ground. The children placed in this category

were not expected to have the notion of space surrounding the earth. As a result, the drawing of a horizontal line above the circle to depict the sky, or some other indication that the sky is located only above the top of the circle, was the expected response to the question "Now draw the sky" (Response types a and c). Responses which indicated that the sky is below the earth (Response types f and g) were considered unacceptable deviations for the disc model.

Children with disc models were expected to draw the people (Question 8) and Champaign and China (Question 14) inside the circle, and to explain the flat/sphere conflict by saying that the earth is round like a pancake (Question 9, Response type e), like the children in the flattened sphere model. Unlike the flattened sphere model, however, the children who used the disc mental model were expected to say that the earth has an end/edge (Questions 10 and 11), from which people can potentially fall off (Questions 12 and 13), and that there is dirt or ground underneath the earth (Question 15, Response type d). All other responses to Question 15 were unacceptable deviations.

Disc earth data. Only one child met all the criteria for using this mental model consistently. Here is an excerpt from this child's protocol.

Jamie (3rd grade) (Subject number 21, disc model)

E: What is the shape of the earth?
C: Round.
E: Which way do we look to see the earth?
C: I don't know.
E: Well, think about it.
C: Probably in the sky.
E: Can you draw a picture of the earth?
(Child draws the picture appearing in Fig. 2d.)
E: How come here the earth is flat but before you made it round?
C: Just because I thought it was round.
E: So what do you think it is?
C: I think it is round.
E: Then how come it looks flat here?
C: I don't know.
E: Maybe we'll come back to that. If you walked for many days in a straight line where would you end up?
C: Probably in another planet.
E: Could you ever reach the end of the earth?
C: Yes, if you walked long enough.
E: Could you fall off that end?
C: Yes, probably.

At the end of the interview, the child was asked some questions over again.

E: Now I want to go back for just a moment and ask a couple of questions . . . What did you say the shape of the earth was?

C: Round.
E: And we said this is a house on earth and it looks . . .
C: Flat.
E: Now, how can that be?
C: Maybe it's just flat.
E: Maybe it's just flat?
C: The earth.
E: Let's just take some of this (clay). Why don't you make the shape of the earth with this?
C: You mean what I think it is?
E: Yes, whatever you think it is . . .
(Child makes a disc with the clay)
E: Now, can people live here? (On top)
C: Yes.
E: Can they live under here? (Bottom of disc)
C: No.

Rectangular earth model. The expected responses to this category were the same as those expected for the disc model except that the children who used this model should say that the earth is a rectangle or a square in response to Question 1 and draw a rectangle or a square to depict it in response to Question 6.

Children with a mental model of a rectangular earth were expected to say that one should look down, all around, or sideways to see the earth in response to Question 2, with "up" as an acceptable deviation. They should draw the solar objects above the top of the rectangle or inside it, and use a horizontal line to depict the sky (Question 7). They should put the people (Question 8) and Champaign and China (Question 14) inside the rectangle, and they should say that the earth has an end/edge (Questions 10 and 11) from which one could potentially fall (Questions 12 and 13).

Finally, children with a rectangular earth model should say that there is dirt or ground below the earth (Question 15). All other responses to these questions were unacceptable. Question 9 regarding the flat/sphere conflict is not applicable for these children because they never state that the earth is round in the first place.

Rectangular earth data. Only one child was found to meet all of our criteria for consistent use of this model. An excerpt from this child's responses to the earth shape questions is given below.

Donald (1st grade) (Subject number 49, rectangle model)

E: What is the shape of the earth?
C: I don't know.
E: Which way do we look to see the earth?
C: Left.
E: What is above the earth?
C: God . . . .

E: Draw a picture of the earth.
(Child draws the picture appearing in Fig. 2e).
C: I don't know how it looks like. All I know is clouds. It's all blue up there. A rectangle? I mean a long thing like this.
E: This is a picture of a house sitting on the earth and here the earth is flat. Do you think the earth is flat?
C: Mine is too.
E: Show me where the people live.
C: In a house (draws house) on the earth.
E: If you walked and walked for many days in a straight line, where would we end up?
C: In Illinois.
E: What if we kept walking?
C: Past! I don't know!
E: Would you ever reach the edge of the earth?
C: He would.
E: Is there an edge to the earth?
C: Yes.
E: Could you fall off the edge of the earth?
C: No. Because. Yes you will.

Dual earth model. Children were placed in this category if they gave a pattern of responses consistent with the view that there is one earth which is round and located up in the sky and another which is flat and on which people live. Most of the children who constructed this model used the word "earth" primarily to refer to the round earth which is like a planet, up in the sky. The flat earth was usually referred to as "the ground." Understanding the child's terminology is crucial for this model for it explains an apparently inconsistent pattern of responses by a number of children.

We reasoned that the children who hold a dual earth model and use the term "earth" to refer to the round earth should give round earth responses when asked questions which use the term "earth" and flat earth responses when asked questions which do not use this term, particularly generative questions which require children to make use of their everyday experience.

Based on this general hypothesis we concluded that in response to Question 1, "What is the shape of the earth?" children with a dual earth model should say that the earth is a sphere, round, or circle; in response to Question 2, "Which way do we look to see the earth?" they would say "up" because for them the earth should be up in the sky; in response to Question 6, "Can you draw a picture of the earth?" they should draw a sphere or a circle to depict the earth.

Question 7 is a very interesting one for children with a dual earth model. The exact wording of this question is: "Now on this drawing show me where the moon and the stars go. Now draw the sky." There is no use of the word "earth." If we are right in our assumption that the children

who use this model think that they live on flat ground which is below the spherical earth, then they could draw the stars and the moon either above the top of the circle or all around it (Response types a, b, c, and d). Children with this model should not place the moon and the stars inside the circle as is possible for children with a hollow sphere model or a disc model (Response type e).

With respect to the sky, we expected the children in this category to have an experiential understanding of the sky as the area above the top of the flat ground and therefore to use a horizontal line to depict it. This horizontal line could be placed either above the top of the circle or below the circle, but above the assumed flat ground (Response types a, c, f, or g). The dual earth model is the only one where the depiction of the sky using a horizontal line below the circle is a meaningful response (Response types f and g).

Question 8, "Show me where the people live," (which was asked with reference to the child's drawing of the earth) could be a perplexing question from the point of view of a child with a dual earth model who uses the word earth to refer to the round earth but thinks that people live on flat ground. There are two things a child who uses such a model could do. One is to answer the question by showing where he or she thinks people really live. This would generate the response of drawing the people on flat ground outside the circle (Response type c). The other is to give in to the implicit assumption that the people live somewhere on the round earth (Response types a, b, or d). Some children seem to be unsure as to which of these two responses to select. These children start by putting people on the flat ground and then change and place them on the round earth (Response type d). All of the above responses were scored as expected responses. Other responses (e.g., drawing the people on flat ground inside the circle) were considered unacceptable deviations. The same analysis applies to Question 14 about Champaign and China, and therefore the expected responses for this question were either inside the circle or on flat ground outside the circle.

Question 9, "How come here the earth is flat but before you made it round?" is also a confusing question from the point of view of a child with a dual earth model because it refers to what they would call flat ground as "earth," which is not the way many of these children use the word earth. Nevertheless, it gives children the opportunity to say that the round earth is up in the sky and that it looks flat in the picture because the ground is flat (Response type h). An example of this type of response is the following: "The earth is round like a ball. It looks flat down here because it [the picture] doesn't have the ball."

Questions 10 and 11, "If you were to walk for many days would you ever reach the end/edge of the earth?" and "Is there an end/edge to the

earth?" have the same problem as Questions 8 and 9. Here a child can answer the question with respect to the round earth in the sky and say "No the earth does not have an end, but this earth is up in the sky," or can respond with respect to the flat ground and say that there is an end/edge to the ground from which one could fall off (Questions 10, 11, 12, and 13, Response types f and a).

Finally, Question 15, "What is down here below the earth?" (asked with respect to the child's drawing of the earth) could be answered in one of two ways. The child could refer to the flat ground under the round earth and say "ground" or "us." Or, the child could refer to the area between the flat ground and the round earth and say "sky" or mention the sun, moon and stars.

Dual earth data. Eight children were found to use this mental model. All of these children said "round" or "circle" in response to Question 1. As expected, all of them stated that you look "up" to see the earth in response to Question 2. All children drew a circle to depict the shape of the earth in Question 6. In some cases the flat/sphere conflict became evident in the response to this last question. For example, one child drew a rectangle earth first but when he was asked why he had said that the earth is a circle in the previous question said that "he forgot" and drew a circle. A second child drew a circle after asking, "Like it's up in the sky?"

As expected, all the children in this category drew a horizontal line to depict the sky. Most children placed this horizontal line above the top of the circle. Two children placed it below the circle, and another child drew a rectangular sky above the circle and placed the sun and moon inside it.

In response to Question 8, "Show where the people live," many children drew their people either on a flat line outside the circle or on the border of the paper. This response does not make sense from the point of view of an adult who has a spherical earth model and does not understand the dual earth child's use of the term "earth." We were not aware at the time that many children typically used the term "earth" to refer to a separate round earth. We were therefore perplexed by the apparent inconsistency in placing the people on flat ground outside the circle while at the same time insisting that the earth is round. As a result, such a response was often followed by a question from the experimenter who, taking the adult point of view, asked the child, as in the case of Darcy below, "Is that where people live, on the earth?" At this point often the child would change his/her response and put the people inside the circle.

All but two of the children placed in this category gave an explanation of the flat/sphere conflict (Question 9) by saying that the earth which is up in the sky is round but the ground on which we walk is flat. One child (number 51) could not explain the flat/sphere conflict but because she

gave strong indication of a dual earth mental model in other responses, she was still placed in this category. This child drew a flat line under the circle and called it ground. Later on she said that "the ground is underneath the earth" and that "between the earth and the ground there is sky."

Most children in this category said that there is an end/edge to the earth from which one can fall (Questions 10, 11, 12, and 13) and that there is ground or sky below the earth (Question 15). As just mentioned, one child (number 51) made it very explicit that the sky is between the earth and the ground.

The following is an excerpt from the protocol of one child who was placed in the dual earth category.

Darcy (3rd grade) (Subject number 40, dual earth model)

E: What is the shape of the earth?
C: Round.
E: Which way do we look to see the earth?
C: Up.
E: Can you draw a picture of the earth?
C: Round. I can't draw one. (Child's drawing is shown in Fig. 2f.)
E: Now on this drawing show me where the moon and stars go. Now draw the sky.
C: It's icky.
E: Now that's a really good picture. Now show me where the people live.
C: (Child draws house at the border of the paper.)
E: Can you show me in your picture where people live, Darcy?
C: Down over here? (Child draws another house along the same border.)
E: Is that where people live on the earth?
C: Child (giving in to the implicit demands of the experimenter) erases one of the houses and draws a person inside the circle.
E: Here is a picture of a house. This house is on the earth isn't it? How come the earth here is flat but before you made it round?
C: I don't know.
E: Is the earth really round?
C: No.
E: It's not really round. Well, what shape is it?
C: Yaa, it's round.
E: Then how come it looks flat here?
C: Because it's on the ground.
E: But why does that make it look flat?
C: Because the ground's flat.
E: But the shape of the earth is . . . .
C: Round.
E: If you walked and walked for many days in a straight line where would you end up?
C: On earth.
E: Would you ever reach the edge of the earth?
C: No.
E: Why not?
C: Because it's so high.

E: Because what's so high?
C: The earth.
E: Could you fall off the edge of the earth?
C: Yes.
E: Where would you fall?
C: Down on the ground.
E: Where is the ground in your picture?
C: Down here (shows the border of the paper).
E: OK, but this is the earth right? (experimenter points to the circle)
C: Yes.
E: What's this out here? (the border of the paper)
C: Ground.
E: Tell me in this picture what is down here below the earth?
C: Sky.

This protocol is a good example of how a child can look very inconsistent to an adult who does not understand his or her model. At the time of testing Darcy appeared to be very inconsistent to the experimenter who was questioning her. Yet, she is very consistent in her use of a dual earth mental model, using the term "earth" to refer to the round earth only.

Mixed models. The earth-shape categories discussed so far were identified a priori based on information provided by earlier research in this area (e.g., Nussbaum, 1979; Nussbaum & Novak, 1976) and by an examination of the data. By using these categories we were able to account for 49 out of our 60 subjects. The remaining 11 subjects were put in a mixed category which is described below.

Five of these children gave responses which were consistent with either a spherical or an alternative model of the earth but did not pass our strict criteria for placement in these models. One child (Subject 12) was quite sophisticated in his responses but had particular difficulty explaining the flat/sphere conflict and kept changing his mind about whether the earth has an end/edge or not. Subject 23 at first seemed to have a hollow sphere model, but upon further questioning it appeared that she may have been conceptualizing the earth as a truncated sphere. Subject 17 was close to a flattened sphere model and Subject 54 gave responses consistent with a dual earth model, but both had more deviations than those allowed by our scoring system and could not, therefore, be assigned to these categories. Similarly, Subject 47 had responses consistent with a dual earth model but at the end of the interview changed his mind and adopted the view that the earth is flat like a disc.

The remaining six subjects gave apparently inconsistent responses that fit none of our models, nor could we devise plausible additional models that would account for their patterns of responding.

Frequency of earth shape mental models. Table 4 shows the frequency of the identified earth shape mental models by grade.

TABLE 4
Frequency of Earth Shape Models as a Function of Grade

	Earth shape models	Grade 1	Grade 3	Grade 5	Total
1.	Sphere	3	8	12	23
2.	Flattened sphere	1	3	0	4
3.	Hollow sphere	2	4	6	12
4.	Dual earth	6	2	0	8
5.	Disc earth	0	1	0	1
6.	Rectangular earth	1	0	0	1
7.	Mixed	7	2	2	11
Total		20	20	20	60

As can be seen, there is a developmental progression of the models held by these children. Most 1st-grade children held a dual earth mental model or a mixed model. The 3rd-grade children held a wide range of mental models including sphere, hollow sphere, and flattened sphere. Most of the 5th graders have adopted either the sphere model or the hollow sphere model. These data clearly show the gradual impact of cultural information about the shape of the earth on children's initial flat earth models.

Test of Mental Model Consistency

Our basic strategy in the analysis of these data has been to propose that the children in this study adopted a small set of mental models about the shape of the earth and then to see how much of the variation in children's individual responses to the earth shape questions could be explained by assuming that the children were consistent in their use of these mental models. Indeed, the results of our analysis showed that we could account for 82% (49 out of 60 subjects) of our data by assuming that the subjects used these models in a consistent fashion.

This approach raises a critical question. Is the observed consistency real or an artifact of our scoring procedure? More specifically, is it possible that our criteria for assigning children to the various earth shape categories were loose enough to generate consistency from a pool of random responses to the same questions?

In order to test this possibility we took the responses for each individual earth shape question and randomly reassigned these responses across the subjects. Using this procedure we ended up with a pool of data consisting of the same set of responses for each question but with the responses randomly reassigned to the subjects. We then followed the same

procedure we had followed before to assign mental models to children using the reassigned data.

The results of this reclassification appear in Table 5. As can be seen, the distribution of subjects to earth shape categories in the randomly assigned data is quite different from the distribution of subjects to earth shape categories in the obtained data. In the great majority of the cases we were not able to identify a well-defined and consistently used pattern in the randomly assigned data; only 23% of the subjects could be assigned to an earth shape category other than the mixed one. Using a χ^2 statistic we found a significant difference between the number of children assigned to models in the actual data and in the random data, $\chi^2(1, N = 60) = 114.13$, $p < .001$.

The Possibility of Question Bias

We have been arguing that a great deal of the inconsistency in the data can be explained by assuming that the children in our sample used in a consistent fashion a small number of well-defined mental models of the earth. In this section we would like to consider a second critical question raised by our data. It has to do with the possibility that our questions biased the results.

Earlier we noted how Darcy, the 3rd grader with a dual earth model, changed her response to comply with the assumption implicit in our question that the people live "on the earth." Is it possible that our results are in some way biased because the children confabulated their responses to agree with the assumptions implicit in our questions?

The work of Siegal (1991) has shown that children are highly sensitive to the social requirements of experiments and that they often change their

TABLE 5
Frequency of Earth Shape Models in the Randomly Assigned Data as a Function of Age

		Grade			
	Earth shape models	1	3	5	Total
1.	Sphere	1	3	3	7
2.	Flattened sphere	1	0	1	2
3.	Hollow sphere	2	1	1	4
4.	Dual earth	0	0	0	0
5.	Disc earth	0	0	1	1
6.	Rectangular earth	0	0	0	0
7.	Mixed	16	16	14	46
Total		20	20	20	60

responses in conditions of repeated questioning to comply with the implicit demands in the questions.[2]

It appears that the extreme interpretation of a bias hypothesis in the present case would be that the consistency in our data is largely a product of our questioning, in other words, the alternative models of the earth are not real, but fabricated by the children who accepted the assumptions implicit in our questions. Exploring this hypothesis requires a careful examination of the assumptions behind our questions to see whether there is a possibility for fabricating the alternative models of the earth by accepting their presuppositions as true.

Even a very superficial look at the questions should show that this extreme form of bias hypothesis is extremely implausible. There are no assumptions implicit in the questions that could, by any stretch of the imagination, give rise to the alternative models of the earth we have discovered. Nowhere is there an implication that there are two earths, that people live inside the earth, or that the earth is flat like a disc or like a flattened sphere.

As was discussed in the method section, the questions were constructed for the purpose of testing the generativity of children's knowledge about the culturally accepted, spherical shape of the earth. This was done by asking questions which created a conflict between the everyday experience of a flat earth and the information coming from the adults that the earth is a sphere. The only alternative models of the earth these questions could encourage would be the flat earth models, which were adopted by only two children.

A less extreme implication of the bias hypothesis would be to argue that the acceptance of the implication of flatness resulted in some spherical earth children appearing inconsistent. It is also possible that we classified some children who have well-defined models of the earth as mixed. Repetition of a question, and therefore the response change this may bring about, occurred usually in situations where the children were providing answers which did not make sense from the adult, spherical earth point of view. It is hard to avoid some bias of this type. Understanding the child's point of view is often extremely difficult to do—the experimenters are often as constrained by the presuppositions of their point of view as the children are. Note, however, that in both cases the possible bias in our questions would lead to *fewer* children classified as holding consistent models.

[2] In fact, repetition of a question alone does not seem to lead to inconsistency. Inconsistency is found when a question is repeated following a transformation, as often happens in a Piagetian conservation task (e.g., Halford & Boyle, 1985; Neilson, Dockrell & McKechnie, 1983).

This analysis of question bias suggests that some of the inconsistency in our sample may be artifactual. We have already noted that about half of the children in our mixed category would have been placed in some well-defined category if our criteria for consistency were not so strict. Thus, question bias in our case would tend to lead to an *underestimate* of consistency, not an overestimate.

DISCUSSION

Mental Models of the Earth

The results of this study showed that the great majority of the children are consistent in their use of a well-defined mental model of the earth's shape. This mental model is not always the culturally accepted sphere model. Only 23 of the 60 children investigated used a spherical earth mental model.

Twenty-six out of the 60 children in our sample used a coherent mental model of the earth which was different from the spherical model. We were able to identify five clear alternative mental models of the earth: the rectangular earth, the disc earth, the dual earth, the hollow sphere, and the flattened sphere. Children with a rectangular earth mental model believe that the earth is flat and shaped like a rectangle; children with a disc earth mental model conceptualize the earth as flat and round. Children who have a dual earth concept believe that there is a round earth which is up in the sky and a flat ground on which people live. Children with a hollow sphere mental model believe that the earth is spherical but that people live deep inside this hollow sphere, while children with a flattened sphere model believe that the earth is shaped like a thick pancake, round on the sides, but flat on the top and the bottom.

Overall, the results of this study agree with the results of prior research (Nussbaum, 1979; Nussbaum & Novak, 1976; Sneider & Pulos, 1983) which show that elementary school children have difficulty understanding that the earth is spherical and form various misconceptions regarding its shape. Our results go further than these studies, however, because we use explicit criteria and a variety of qualitative and quantative measures to show that there are a small number of well-defined alternative mental models of the earth which are used by children in a consistent fashion.

Mental Models: Precompiled or Constructed on the Spot?

It is not clear from the results of this study whether the models we have identified represent precompiled theories which are stored in long-term memory or whether they are constructed by the children on the spot under the influence of our questions. Some children appeared to be very certain about their views and expressed them with such speed and lucidity

that it is unlikely that they constructed them on the spot. In other cases, the sequence of responses to our questions suggests some model construction while answering the questions.

Regardless of how this issue is resolved, the fact that 82% of our data can be explained by assuming that the children were consistent in their use of one of a small set of mental models about the earth strongly suggests that there are some stable underlying conceptual structures which constrain the range of possible mental models that children can form.

Presuppositions Constrain the Formation of Mental Models

Although the adult culture provides massive exposure to the idea that the earth is a sphere, many children believe that the earth is flat and shaped like a rectangle, or like a disc, or that the earth is a sphere but that people live deep inside it. While there may be some limited support for some aspects of these models from the adult culture, we think it is obvious that they are predominantly child-generated. Why do children come up with such dramatic misconceptions regarding the shape of the earth?

We propose that the reason children find it difficult to believe that the earth is spherical is because they are operating under the constraints of certain presuppositions which are inconsistent with the culturally accepted information that the earth is a sphere. What we mean by presuppositions is similar in many respects to Gelman's (1990) principled distinctions, or Spelke's (1991) constraints. They seem to be constructed by the children on the basis of their everyday experience as this experience is interpreted through the human perceptual/cognitive apparatus. These presuppositions act as constraints on the kinds of mental models of the earth that children can form.

One of these presuppositions is that *the ground is flat*. Children seem to believe that if things look flat, they are in fact flat and, therefore, that the ground is flat. All the mental models we have identified are constrained by the belief that the ground on which people live is flat. This is obvious in the case of the rectangular earth model and the disc model where the earth is conceptualized to be flat. In the dual earth mental model there is a round earth which is up in the sky and flat ground on which people live. In the hollow sphere model the earth is seen as a sphere but people live on flat ground inside the sphere. Finally, in the flattened sphere mental model the earth is conceived of as a thick pancake: round on the sides, but flat on the top and bottom where people live. There would be no reason for children to form these systematic misconceptions if they did not believe that the earth is flat in the first place.

Of course, what is meant by "flat" here should be qualified. While the subjects of this study lived on the flat plains of the midwestern United States, where the earth appears to be literally flat, other children, includ-

ing the children in our cross-cultural studies in Greece, Samoa, and India, lived in environments which included high mountains and oceans and showed similar presuppositions. What we mean by "flat" is not the absence of mountains but rather the expectation that the ground extends along the same plane, as opposed to something that forms a sphere. This is not, obviously, the product of a simple phenomenal perception of "flatness," but represents, as do the other presuppositions, the complex interpretation of everyday experience by a constructivist mind.

A detailed examination of the obtained mental models shows that there is at least one additional presupposition which constrains them. This is the presupposition that *unsupported things fall.* This presupposition seems to be derived from children's beliefs about physical objects in general. Research by Spelke (1991) has shown that the general conception that objects require support starts to develop between 6 and 9 months of age. Baillargeon and her colleagues (e.g., Needham & Baillargeon, in press) have provided evidence that even younger infants may be sensitive to certain aspects of the notion that objects require support.

The presupposition that unsupported objects fall seems to be applied first to the earth itself and second to the objects or people on the earth. When applied to the earth, it requires that the earth be supported by something like ground or water. Such a presupposition constrains the rectangular, disc, and dual earth mental models where the place we live is conceptualized as flat supported by ground or water all the way down.

It appears that some children suspend their presupposition that the earth itself requires some support[3] and yet still believe that objects or people on the earth require support. This presupposition makes it difficult for these children to understand how people can live on the spherical earth without falling off. One solution to this problem is for the children to assume that people live inside the sphere, as in the hollow sphere mental model.

Children who adopt the hollow sphere mental model seem to have understood that the earth is a sphere in space but have not yet understood that it is possible for people to live all around this sphere, on the outside, without falling off. The lack of support issue does not present itself in the case of the rectangular, disc, and dual earth mental models, in which people live on the top of flat ground. The flattened sphere mental model is not constrained by this presupposition; the children who formed this

[3] Of course, technically speaking, the earth is falling all the time. What children need to do is to completely reinterpret their conceptions of up/down gravity. It is interesting to note here that in a detailed investigation of the units in astronomy in four popular science series for elementary school children, we did not find a single lesson on gravity associated with the problem of what supports the earth or the people on the earth (Vosniadou, 1991b).

mental model knew that people can live on the bottom of the sphere without falling. However, these children still seem to believe that the ground on which people live is flat and thus flatten the top and bottom of the sphere to be consistent with this presupposition.

To conclude, we have argued that children's difficulty in understanding that the earth is a sphere stems from the constraining effect of two presuppositions: (a) the presupposition that the ground is flat and (b) the presupposition that unsupported things fall. These presuppositions appear to be part of a more general theory of naive physics which filters children's interpretations of the physical world and constrains their mental models of the earth.

Initial Mental Models of the Earth

If we are correct that mental models are constrained by certain presuppositions, then we should expect that the first, initial mental models children form, before they are exposed to any information from the adult culture, should be constrained by the set of presuppositions just discussed. As a result we should expect children to conceptualize the earth as consisting of flat ground with people living on top of it and to believe that this ground extends all the way down below the earth. We assume that children do not have the notion of an infinite plane and thus conceptualize this flat ground to have an end or an edge.[4] An additional inference regarding the nature of the edges of this flat ground can produce a class of mental models according to which the flat earth can be conceptualized to be shaped like a rectangle, a square, or a disc.

Although only two children produced this kind of mental model in our sample (one rectangular and one disc), we have obtained additional evidence for the presence of such initial models in our studies of preschool children (in progress) and in our cross-cultural studies (Brewer, Herdrich, & Vosniadou, 1987; Vosniadou, Archodidou, & Kalogiannidou, submitted for publication; Vosniadou & Brewer, 1989; Samarapungavan & Vosniadou, 1988).

Synthetic Mental Models of the Earth

The other mental models of the earth we have identified can be explained as attempts on the part of the children to reconcile their presuppositions with the information they receive from the adult culture that the earth is a sphere. By forming these synthetic models children try to as-

[4] Clearly, children do not have any actual experiences of walking to the end of the earth. We assume that because children have prior experiences with other objects having ends or edges, but not with the notion of infinite space, they would be likely to conclude by analogy that the earth also has an edge.

similate the information that the earth is a sphere with their preexisting knowledge structures in a way that allows them to retain as many of their presuppositions as possible.

The dual earth mental model is a good example of this process. The children who have formed this mental model have retained all of the presuppositions that give rise to an initial model. These children answer our questions in a way that shows that they still believe that the ground is flat, that there is ground all the way down below the earth, and that things fall in a downward direction. Children with this mental model reconcile the information that the earth is spherical with their presuppositions by assuming that adults refer to a different object when talking about the round earth.

Another solution is to revise some of these presuppositions. The revision of a presupposition can be done when a child understands that sometimes big round things can appear to be flat, or understands how gravity "supports" the earth or the people who live on the spherical earth. The revision of a presupposition frees children from the constraints this presupposition imposes on the kinds of mental models that they can form and allows them to form a new class of mental models. An examination of the synthetic mental models we have identified suggests that there may be a progression from simpler to more advanced synthetic models, depending on how many presuppositions have been revised.

As we have already seen, the dual earth is the simplest synthetic mental model because it does not require any presupposition revision. Next comes the hollow sphere model, which requires changing the presupposition that the earth needs to be supported by something like ground or water. The removal of this constraint allows the child to conceptualize the earth as suspended in space. The presuppositions that the ground is flat and that the people who live on the earth need to be supported continue to operate, however, constraining the nature of the types of suspended earth models that are possible. The hollow sphere mental model with people living on flat ground deep inside the sphere reconciles the adult, scientific model of a spherical earth with the child's presuppositions that the ground is flat and that objects on the earth fall when they are not supported.

The flattened sphere mental model is the most sophisticated synthetic model of the earth. Children who hold this model know that gravity keeps people on the spherical earth. These children retain only their belief that the ground is flat. In order to reconcile this belief with the information that the earth is a sphere, they conceptualize the spherical earth as flat on the top and bottom and imagine that people live on these flat areas.

The data on the frequency of earth shape models by grade (shown in Table 4) is in general agreement with this theoretical analysis in terms of

presuppositions. The models that require the fewest changes (e.g., the dual earth model) are more frequently found in the youngest children, while the models that require the largest number of changes (e.g., the sphere) are more frequent in the oldest children.

Consistency versus Fragmentation

The success in identifying consistent mental models for the great majority of children in our sample shows that children's conceptual knowledge is not as fragmented and unconnected as some theorists have argued (e.g., diSessa, 1988; Solomon, 1983). It appears that children try to synthesize the information they receive from adults and from their everyday experience into coherent mental models which they use in a consistent fashion.

The arguments in favor of the position that children are self-contradictory and inconsistent often do not take into consideration that what may appear as contradictory and inconsistent from the adult or expert point of view may not be contradictory from the point of view of the child (Brewer & Samarapungavan, 1991; Wiser, 1988). Nevertheless, while our data indicate that children are capable of forming well-defined mental models and of using them in a consistent manner, more research is needed using more complex concepts and in many other domains in order to establish the generality of this finding.

Conceptual Change Involves Theory Restructuring

Conceptual change has often been thought of in terms of the differentiation and hierarchical integration of children's initial conceptual structures. This proposal put forward originally by Werner (1948) has found many proponents in recent years (Keil, 1979, 1983; Smith, Carey, & Wiser, 1985; Carey, 1985; Chi, 1988), although there are important differences in the way that differentiation and hierarchical integration are conceptualized by different researchers. Tree branching or tree switching (Thagard, 1992) and change between ontological categories (Chi, 1992) are other mechanisms that have been proposed to account for conceptual change.

There is no doubt that tree branching or tree switching, differentiation and coalescence, and change between ontological categories are important forms of conceptual change. However, the change from an initial mental model of a flat earth to the culturally accepted mental model of a spherical earth cannot be accounted for in terms of the above-mentioned types of changes. Nor can it be accounted for by a model such as the one proposed by Chi (1988) in which two separate and previously unconnected microstructures become hierarchically organized. Assuming that the information that the earth is a sphere is originally stored as a separate

microstructure, Chi's model can explain how the dual earth mental model is formed, but it cannot explain how children generate the hollow sphere or flattened sphere models.

If we are correct in our assumption that children's mental models of the earth are constrained by certain presuppositions, then what is needed for conceptual change to occur is the reinterpretation of these presuppositions. As was mentioned before, children need to understand how round things can sometimes appear to be flat and how gravity "supports" the spherical earth and the people who live on it. It is important to note that when the explanatory framework for a presupposition changes, the observation that in the everyday world the ground is flat or that unsupported things fall does not change. What changes is the interpretation of this observation. This type of change in explanatory framework in children has been discussed previously by Carey (1985) and is also an important characteristic of theory change in the history of science (Kuhn, 1970; Lakatos, 1970; Laudan, 1977; Toulmin, 1972).

METHODOLOGICAL CONSIDERATIONS

The methodology used in this study was based on the initial assumption that children are active theory builders and that they are likely to construct initial mental models about the world which are consistent with their everyday experience (Piaget, 1929). This assumption provided us with some hypotheses about the possible nature of children's initial mental models and the areas where these initial mental models could differ from the culturally accepted, scientific models. We were then able to generate questions that allowed us to differentiate between the hypothesized initial mental models and the scientific models.

We asked a wide range of questions (see also Keil, 1979; Gelman, 1991) and then checked to see whether the individual responses to these questions were consistent with respect to a hypothesized model. Of particular interest are the kinds of questions we call generative. These are questions about phenomena which children cannot directly observe and about which they are not likely to have received any direct instruction. These questions have the potential of revealing the kinds of mental models children are using.

Another methodological consideration of interest is the procedure for checking the consistency of the obtained mental models. This was done by hypothesizing a particular mental model and then examining the pattern of responses to see if they could be generated by assuming a consistent use of this model (cf. Siegler, 1978, for a similar approach).

Finally, it is important to note that this type of developmental research has produced methodologies that allow us to go from complex qualitative information to a limited number of well-defined models which are reliable

and consistent with the protocol data. Approaches such as these make it possible to use protocol data to make inferences about underlying cognitive structures.

CONCLUSIONS

We have argued that children form an initial mental model of a flat earth which is constrained by a set of presuppositions which seem to be derived from everyday experiences and which are consistent with their beliefs about inanimate physical objects in general. The process of changing from this initial mental model to a mental model of a spherical earth is slow and gradual and gives rise to intermediate synthetic models of the earth. Synthetic models are formed when children try to reconcile the information coming from adults that the earth is a sphere with their presuppositions. In order to form the culturally accepted, scientific mental model of a spherical earth, children must reinterpret their presuppositions within a different explanatory framework.

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